JOINT PAINT REMOVAL STUDY

JOINT POLICY COORDINATING GROUP ON DEPOT MAINTENANCE

TASKING DIRECTIVE 1-90

FINAL REPORT ON

HIGH-PRESSURE WATER BLASTING

FOREWORD

This report is the fourth of five individual studies directed by the Joint Policy Coordinating Group on Depot Maintenance in Tasking Directive 1-90. It is an evaluation of paint stripping methods using water blasting. Advances in water blasting technology have resulted in specific pressure divisions: medium-pressure water (MPW) is 8,000 to 15,000 pounds per square inch (psi) and high-pressure water (HPW) is pressure above 15,000 psi. A primary difference between MPW and HPW is the means of media delivery. For MPW blasting, media is usually delivered manually with a hand-held nozzle. On the other hand, HPW media delivery is almost exclusively automated.

This program evaluated paint stripping using water blasting. The Air Force did most of the testing at Oklahoma City Air Logistics Center (OC-ALC), Tinker AFB, OK, and Sacramento Air Logistics Center (SM-ALC), McClellan AFB, CA, on various aircraft and components. The Navy also developed a system for use on ship and submarine hulls. The goal of this program was to determine if water blasting could meet or exceed established performance criteria for productivity versus possible blast imparted substrate damage and to evaluate the quality of the stripped surface.

The points of contact for the Joint Paint Removal Study are listed in Appendix III.

EXECUTIVE SUMMARY

BACKGROUND:

On 19 Dec 89, The Joint Policy Coordinating Group on Depot Maintenance (JPCG-DM) tasked the Joint Technology Exchange Group (JTEG) to study alternative paint removal processes that have potential use within the Department of Defense (DOD) depot maintenance community (Tasking Directive 1-90, Appendix I). The JTEG was then directed to plan and manage the study, identify the techniques to be used, sponsor/advocate necessary research and development initiatives, oversee joint Service testing, evaluate the study, and report the results.

OBJECTIVE:

The objective of the study is to provide managers coordinated joint Service technical and management information to help them make investment and application decisions pertaining to current and emerging paint removal processes. This study identified and evaluated alternative paint removal processes to eliminate duplicate developmental and testing efforts.

SCOPE:

To realize the quickest benefits, the JTEG studied only the five most prominent paint removal alternatives being developed to replace chemical stripping: plastic media blast (PMB), laser, sodium bicarbonate blasting, carbon dioxide pellet blasting and high-pressure water blasting. To reduce costs and time frames, tests were conducted at facilities that had already established or begun to establish organic capability.

STUDY PLAN: The study was conducted in three phases.

Phase I was a comprehensive review, within DOD, to identify existing capabilities/plans and to establish a baseline for the study. The baseline, which related to the five alternatives, identified capabilities, the degree of maturity of each method, developmental efforts and time frames, and study criteria. Also, from the baseline data, lead activities were recommended and study teams established.

Phase II covers the feasibility study, testing, and analysis, which began when the JTEG designated lead activities and developed a coordinated plan for each process to include economic, environmental and technical evaluations. During this phase, the status of each alternative process was reported periodically to the JPCG-DM and the depot maintenance community.

Phase III involves analyzing and documenting the processes. As each process is tested an interim report will be provided. When studies are complete, a final report will be published and disseminated within DOD.

SUMMARY:

Although high-pressure water paint stripping has been used in full-scale production in limited applications in the aerospace industry, it is still considered an emerging technology. Process variables such as optimum blast angles and surface preparation techniques have yet to be authoritatively determined.

Sacramento ALC accepted "lead depot" responsibility for thin skin aircraft application. However, Oklahoma City ALC also conducted a study for thin skin aircraft applications. This study summarizes the two reports. Battelle Corporation developed the SM-ALC report and the OC-ALC report was developed by United Technologies, USBI Company.

Additionally, the Navy, through the Naval Surface Warfare Center working in cooperation with the Air Force, has developed a closed-loop system for use on heavy iron applications. Although this study does not include a formal Navy study, a summary has been provided that lists points of contact and provides general information about the system.

In addition to its limited use on delicate substrates high-pressure water blasting has other drawbacks, such as the requirement for dedicated facilities, special equipment, and containment and filtration systems for expended media.

Because high-pressure water blasting is still an emerging technology, testing continues to determine optimum spray nozzle design, pressure ranges, and blast angles, and the need for or the benefits of including abrasives with the water media.

High-pressure water blasting generates much less hazardous waste than chemical stripping. The only hazardous wastes produced are paint chips and metal in the spent media. Processes are available to filter these wastes out of the spent media. The processes allow the media to be recycled, greatly reducing the quantity of hazardous waste requiring disposal.

Test results indicate that high-pressure water blasting is either better than or equivalent to chemical stripping. There is no increase in fatigue crack growth rate (FCGR) or corrosion, and no adverse trends in post process paint adhesion or spot weld integrity.

Despite the fact that high-pressure water blasting is still in its infancy, test results indicate that it holds promise and the developmental processes for production use should continue.

TABLE OF CONTENTS

SECTION I - OVERVIEW OF HIGH-PRESSURE WATER BLASTING

1.1 INTRODUCTION

1.1.1 Paint and various other types of coatings are necessarily applied, maintained, removed, and replaced in military applications for a variety of reasons. They provide identification and markings, corrosion and thermal protection, visual and electromagnetic camouflage, erosion resistance, and decoration.

1.1.2 Chemical paint removal has been the dominant paint stripping method since the introduction of methylene chloride. When introduced, the technology was highly effective against the predominant topcoats in use (zinc chromate, lacquer, and enamel). Even as the military Services upgraded their coating systems and improved topcoats became available, the traditional methylene chloride-based paint strippers remained in the forefront of paint stripping technology by adding various activators (phenols, formic acid and amine) to enhance removal capabilities. However, the disadvantages of using methylene chloride-based chemical strippers (long processing time, expensive and hazardous chemicals, personnel exposure, safety, and special disposal methods) eventually led to a search for a safer, more effective paint removal technique. Of these disadvantages, the ecological problems of disposing of the hazardous waste stream created as a result of the methylene chloride-based paint strippers finally mandated their discontinuance. Consequently, the Services were forced to step up their efforts to find acceptable alternative paint stripping technologies.

1.1.3 The alternative studied in this report, high-pressure water blasting is still an emerging paint removal technology. Therefore, the processes documented vary from preconditioning or softening the paint before blasting to blasting unconditioned paint with water only.

1.1.4 Although the high-pressure water blasting is not likely to cure all paint removal problems, it shows promise for most applications. However, because the Services have yet to establish optimum process parameters, further testing will be required to determine minimum, optimum, and maximum applications.

1.2 DEFINITION OF HIGH-PRESSURE WATER BLASTING

High-pressure water blasting is a method of stripping and cleaning weapon systems by forcibly projecting a stream of water against their surfaces.

1.3 HISTORY OF HIGH-PRESSURE WATER BLASTING

1.3.1 Although high-pressure water has been used in a variety of maintenance related activities (primarily cleaning, cutting, and stripping), it remains an experimental process as it relates to stripping paint from DOD weapon systems. In 1987, high-pressure water (both water only and grit injected processes) was first used in a production mode by the National Aeronautic and Space Administration (NASA) to strip paint and other materials from various parts of the space shuttle solid rocket boosters. NASA used pressures from 22,500 to 30,000 pounds per square inch (psi).

1.3.2 According to Tasking Directive 1-90, Appendix I, the Joint Technology Exchange Group (JTEG) initiated a project to monitor depot progress in exploring high-pressure water paint stripping. SM-ALC became the lead depot for thin skin applications in June 1990. The thin skin application research eventually evolved into the evaluation of three prototypes; the Aqua Miser®, the Water-Jet depaint system, and the Large Aircraft Robotic Paint Stripping (LARPS) system.

1.4 APPLICATIONS FOR HIGH-PRESSURE WATER BLASTING

1.4.1 High-pressure water can remove coatings from air and ground vehicles, as well as sea vessels. Paint can be either completely removed or merely sheared off in layers by modulating water. Specific applications dictate the pressures, blast angles, and standoff distances.

1.4.2 Each application requires a dedicated blasting environment, a completely enclosed facility to house blasting equipment, such as the water pumps and spraying devices, and a water recovery system used to collect, filter, and recycle the blast media.

1.5 SM-ALC TEST PROGRAM

1.5.1 Purpose. The purpose for SM-ALC's developmental effort was to reduce the volume of hazardous material being treated before being released into the environment.

1.5.2 Rationale.

1.5.2.1 Over the past few years the Air Force has been actively engaged in evaluating and developing alternative methods for aircraft paint removal, an integral part of aircraft repair and overhaul. Current chemical-based paint removal methods are labor intensive and costly because of the required waste stream treatment. Also, due to environmental and health

issues, the use of phenolic, methylene chloride-based paint strippers is being discontinued or severely restricted within DOD.

1.5.2.2 The adoption of new paint stripping processes needs, if possible, to be “transparent," maintaining, or improving the weapon system's function, reliability, and maintainability. This program was initiated to validate the application of low- to medium-pressure water blasting technology and low-toxicity paint softeners to strip primers and topcoats from aircraft skin materials.

1.5.3 Background and Scope.

1.5.3.1 The SM-ALC Aircraft Division was scheduled to receive KC-135 aircraft overflow workload from the OC-ALC, the depot primarily responsible for managing and maintaining the KC-135. Part of depot level maintenance for the KC-135 includes stripping paint from the aircraft's skin. Due to California's environmental and health issues associated with the use of phenolic, methylene chloride-based paint strippers, SM-ALC implemented full-scale PMB facilities to remove paint from aircraft in 1986.

1.5.3.2 Material effects studies, performed by an independent contractor on the PMB process, showed the process could potentially reduce substrate fatigue life and induce residual stresses in aluminum skins 0.071-inch thick or less. Therefore, the KC-135 system manager denied SM-ALC the use of PMB, because the KC-135 has several areas constructed with skins thinner than 0.071-inch. An engineering evaluation was then requested to determine whether removing paint by water blasting, with and without low toxicity paint softeners, would degrade the reliability of KC-135 skins. The program's scope included testing specific materials on panels of 0.032-inch thick, 2024-T3 and 7075-T6 bare and anodized (clad) aluminum following low- and medium-pressure water paint removal with and without chemical softeners.

1.5.4 Conclusions and Recommendations.

1.5.4.1 Any appraisal of the processes reviewed in this report, if based strictly on the face value of the data developed in this study, probably would indicate that SM-ALC would accept neither the low- nor the medium-pressure water processes to remove paint from the KC-135 aircraft. Data shows that both processes highly degrade fatigue life of bare alloy materials. The low-pressure water (LPW) process showed a significantly increased fatigue crack growth rate (FCGR) for all materials tested. In addition, the observed trends suggest the possibility of process-specific effects on materials' crack growth resistance. Because the chemical paint softener used for this study was inconsistent, significant doubts about the veracity of the fatigue data, and possibly the FCGR data, were raised. The doubts centered on possible detrimental effects on the materials produced by standard specimen preparations

and the artificial aging of the coating system. Previously unconsidered, these possible effects could be a significant variable for future test purposes. However, this study has cast enough doubt on the viability of the fatigue and FCGR studies to preclude reliably determining whether either process has truly degraded the test materials.

1.5.4.2 In addition to these issues, the paint softener selected for this study was erratic in terms of expected performance. Consequently, the operational envelope for successful use of the product is not yet fully defined.

1.5.4.3 The LPW process appears to be the better of the two processes, evaluated in terms of paint stripping or productivity. However, neither process can be recommended for implementation without some resolution of the critical issues raised in paragraph 1.5.4.1. The MPW single orifice rotating nozzle may prove to be the most productive nozzle examined in this study. If further testing is undertaken, DOD may benefit from investigating this process.

1.5.4.4 If SM-ALC or other DOD agencies wish to clarify the issues regarding the fatigue and FCGR tests, a seemingly feasible approach would be to test materials that were not treated in any manner whatsoever, except for experimental conditioning. If the materials were tested in this fashion, all variables linked to specimen preparations would be eliminated. The only variables addressed, therefore, would be those germane to the process under evaluation.

1.5.4.5 The issues this study raised do not repudiate the fundamental concept being evaluated, but provide directions for accurately and reliably developing the process.

1.6 OC-ALC TEST PROGRAM

1.6.1 Purpose.

The purpose of OC-ALC's tests was to validate the effects of high-pressure waterjet paint stripping on structural and other performance critical properties of selected metallic substrates and aircraft panels. The successful completion of the test segment supports process certification and process implementation at OC-ALC for stripping large aircraft such as the B-52, KC-135, E-3, and B-lB.

1.6.2 Background and Scope.

1.6.2.1 During process validation testing on metals, parameters established during optimization tests on metals were used to process test coupons, and the effects of the high-pressure waterjet process on metals and aircraft panels were experimentally evaluated. OC-ALC followed a structured approach to generate the materials data required to certify the high-pressure waterjet process for the LARPS system. The test plan was performed according to the Contract Deliverable Requirements List (CDRL), item 018,

and the process viability test plan was delivered as part of the Joint Paint Removal Study (JPRS) test plan.

1.6.2.2 Process validation testing on metals consisted of two major subtasks: process characterization and additional materials testing. The objective of process characterization was to characterize, in detail, the effects of the high-pressure waterjet process on selected critical substrates. During this task, the process effects were evaluated using the following tests:

- **fatigue - unnotched 100,000 cycles**
- **fatigue - unnotched 500,000 cycles**
- **fatigue - notched front 100,000 cycles**
- **fatigue - notched back 100,000 cycles**
- **FCGR**
- **salt fog corrosion**
- **repaintability**
- **water intrusion**
- **spot weld integrity**
- **sealant integrity**

Typical aircraft substrates and coating systems presently being chemically stripped at OC-ALC were used. Aluminum substrates included 2024-T3 anodized (clad), 2024-T3 bare, 7075-T6 clad, and 7075-T6 bare, all having a nominal thickness of 0.032-inch. The coating systems included Koroflex primer (P/N 823X439) and Military Coating Specification (MIL-C) 83286 polyurethane topcoat.

1.6.2.3 The objective of additional materials testing was to validate the efficiency of high-pressure waterjet stripping on numerous metal substrates using coating systems identified in CDRL-018. These substrates included aluminum, steel, stainless steel, magnesium, and titanium. The coating systems included polysulfide primer, waterborne epoxy primer, and self-priming topcoat.

1.6.2.4 For all test evaluations, the effects of the high-pressure waterjet process were assessed by comparing the high-pressure waterjet data to the data from as-received, unprocessed test coupons and painted, chemically stripped test coupons. The test results were evaluated to support certification of the high-pressure waterjet process as an alternative paint removal process and to support implementation of the LARPS system.

1.6.3 Conclusions.

1.6.3.1 This report presents the interim test results from the process validation testing for metals. Tests completed to date include unnotched fatigue at 100,000 cycles and 500,000 cycles, FCGR, corrosion, repaint-ability, spot-weld integrity, and additional materials testing. Remaining tests include notched front and back fatigue, sealant integrity, and water intrusion.

1.6.3.2 Based on the testing completed to date, the high-pressure waterjet process does not adversely affect the mechanical or performance properties of critical aluminum alloys or

structures. Their fatigue life is equal to or better than those stripped with the current chemical process. The FCGR is not increased compared to chemical stripping. The salt fog corrosion behavior and post-process paint adhesion are equal to chemically stripped aluminum. The impact forces of the high-pressure waterjet do not affect the integrity of spot welds typically found on the KC-135 aircraft.

1.6.3.3 Based on the test data generated during the Process Validation Testing, the high-pressure waterjet process is a viable alternative process for implementation in the LARPS system.

1.7 NAVY TEST PROGRAM

1.7.1 Purpose.

The purpose of the Navy project was to design, develop, and demonstrate an automated, full recovery and recycling high-pressure waterjet paint removal system for ships that has minimal environmental impact.

1.7.2 Background and Scope.

1.7.2.1 Environmental issues and regulations are prohibiting continued use of open-air grit blasting to remove ship coatings in drydocks. These issues are related to the release, into air or water, and disposal of heavy metals used in marine coatings (copper, cadmium, lead, etc.). The traditional coating removal methods have been severely restricted by regulations such as the Federal Water Pollution Control Act, the Water Quality Act of 1987, and the Clean Air Act and its amendments.

1.7.2.2 The technical challenges to comply with these environmental regulations are formidable. Any solution must simultaneously contain virtually 100 percent of the process effluent yet be rugged and flexible enough to operate in a drydock. To this end, the U.S. Air Force and the U.S. Navy have joined forces to produce a waterjet demonstration system for use in naval shipyards. This system is based on the Air Force's LARPS research with adaptations to meet specific Navy requirements.

1.7.2.3 The Navy approach was to integrate pieces of laboratory demonstrated, custom design, off-the-shelf hardware into a single system to demonstrate complete removal and recovery of marine coatings. The project passed through design, fabrication, verification testing, and demonstration phases. The demonstration system is now in production, removing coatings on active Navy ships.

1.7.3 Conclusions.

1.7.3.1 Although the process parameters had not yet been optimized, the removal rate achieved during testing was 136 ft^2 per hour. This rate does not include time to move the

manipulator from location to location on the hull; it only includes the time to remove paint from a 4.5- by 6.5-foot envelope. Because the frame only takes a few minutes to reposition, its time is not included in any of the rates mentioned in this section.

1.7.3.2 The vacuum recovery shroud performed extremely well and, after some minor adjustments, it recovered 100 percent of the effluent. An unexpected benefit was that the bare metal did not flash rust following paint removal. This was a result of the strong vacuum and heat created by the water energy (about 120° F), which causes the steel to dry very quickly and eliminates the potential for flash rusting on the surface.

SECTION II - TEST PROGRAM DESCRIPTIONS

2.1 SM-ALC TEST PROGRAM

2.1.1 Summary.

2.1.1.1 The substrates tested were typical aircraft skin materials, 2024-T3 and 7075-T6 bare and clad aluminum alloys. Various panels of each alloy were prepared with coating systems equal to those applied to KC-135 aircraft. These panels were prepared according to Air Force Technical Order (T.O.) 1-1-691, <u>Aircraft Weapons Systems Cleaning and Corrosion Control</u>, and painted according to T.O. 1-1-8, <u>Application and Removal of Organic Coatings, Aerospace Equipment</u>. The coating systems were:

- **Military Primer Specification MIL-P-23377 epoxy primer and MIL-C-83286 polyurethane topcoat.**
- **MIL-P-85582 waterborne epoxy primer and MIL-C-83286 polyurethane topcoat.**
- **Federal Specification TT-P-2760 urethane primer and MIL-C-83286 polyurethane topcoat.**
- **MIL-P-87112 polysulfide primer and MIL-C-83286 polyurethane topcoat.**

2.1.1.2 All painted panels were post cured for seven days at room temperature and artificially aged at 210° F for 96 hours. Dry film thickness measurements were made on all painted panels (both primer and topcoat) to make sure that coating thickness conformed to those specified in T.O. 1-1-8. Painted panels were shipped to SM-ALC for paint removal. Panels were treated with various chemical paint softeners and the paint was removed using a Stonage RJV2 two orifice rotating nozzle and a WOMA Company nozzle for the LPW phase of the program. A fan nozzle and a single orifice rotating nozzle from Carolina Equipment and Supply Company were used for the MPW process evaluation (initial evaluation only). After process optimization, the specimen panels were stripped at the optimized parameters and returned to Battelle for specimen preparation and subsequent testing.

2.1.1.3 Four paint softeners were evaluated initially. These were TURCO 6813, Fine Organic FO 630, Fine Organic CB-1058 and Eldorado SR125A for the full evaluation.

2.1.2 Test Specimens.

Test specimens consisted of standard and notched fatigue life, center-notched FCGR and Almen type specimens. Figure 1 shows the test matrix. All specimens (baseline and experimental) were sectioned from the test panels with the longitudinal axis in the rolling direction of the sheet. Figures 2, 3, and 4 show examples of the test specimen layout for a 2024-T3 bare sheet. Layouts for the other alloys were identical.

			Number of Specimens		
Test Speciman	Loading	Material	Baseline	Stripped	
Crack Growth	Constant Amplitude	2024-T3 Bare 0.032"	10	10	
	Constant Amplitude	2024-T3 Clad 0.032"	10	10	
	Constant Amplitude	7075-T6 Bare 0.032"	10	10	
	Constant Amplitude	7075-T6 Clad 0.032"	10	10	
Fatigue Life (Standard ASTM) Untouched	Constant Amplitude	2024-T3 Bare 0.032"	10	10	
	Constant Amplitude	2024-T3 Clad 0.032"	10	10	
	Constant Amplitude	7075-T6 Bare 0.032"	10	10	
	Constant Amplitude	7075-T6 Clad 0.032"	10	10	
				Front	Back
Fatigue Life (Surface Notched)	Constant Amplitude	2024-T3 Bare 0.032"	10	10	10
	Constant Amplitude	2024-T3 Clad 0.032"	10	10	10
	Constant Amplitude	7075-T6 Bare 0.032"	10	10	10
	Constant Amplitude	7075-T6 Clad 0.032"	10	10	10

Figure 1. Test specimen fabrication and test matrix.

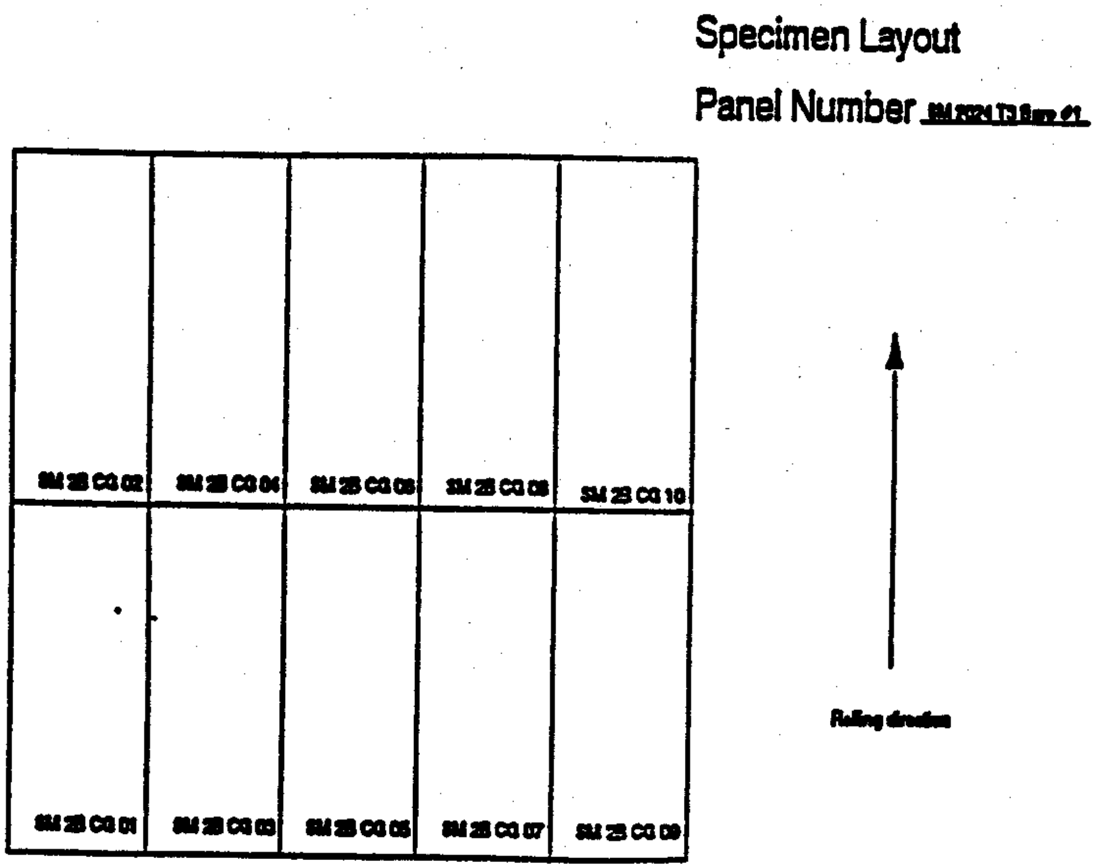


Figure 2. Specimen layout for crack growth rate.

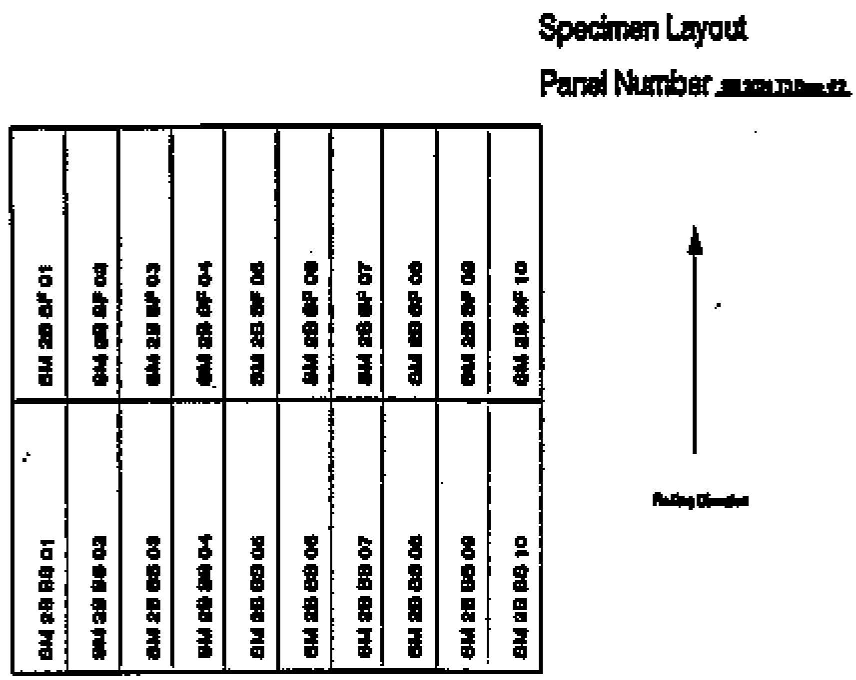


Figure 3. Specimen layout for unnotched fatigue.

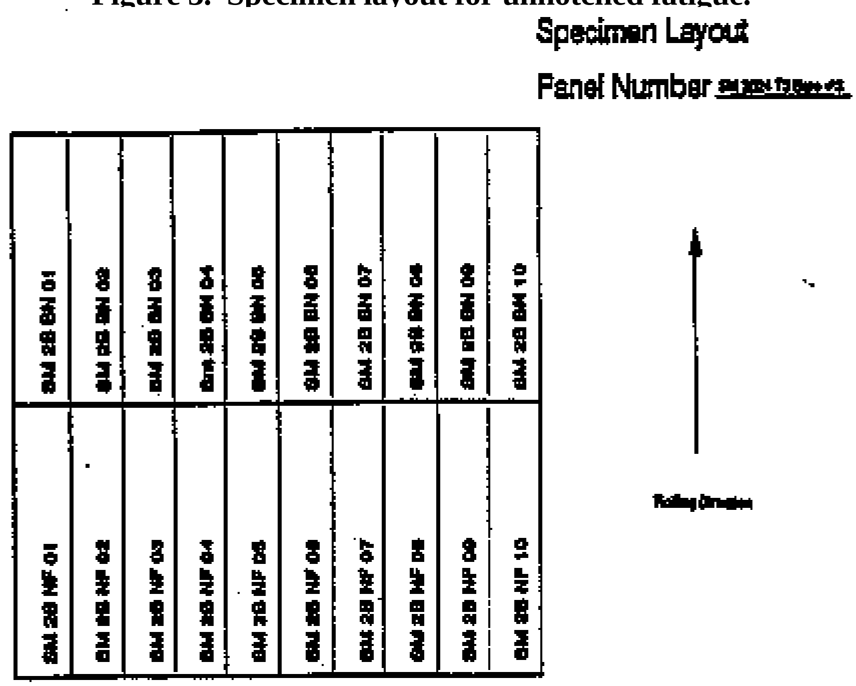


Figure 4. Specimen layout for notched fatigue.

2.2 OC-ALC TEST PROGRAM

The ALC conducted a detailed materials test program to evaluate the effects of the high-pressure waterjet process on various metallic substrates. Figure 5 shows the process optimization and validation testing roadmap. Typical aircraft substrates and coating systems presently being chemically stripped at OC-ALC were used. The following paragraphs describe the metals, coating systems, surface preparation materials, paint stripping methodology, and the tests performed.

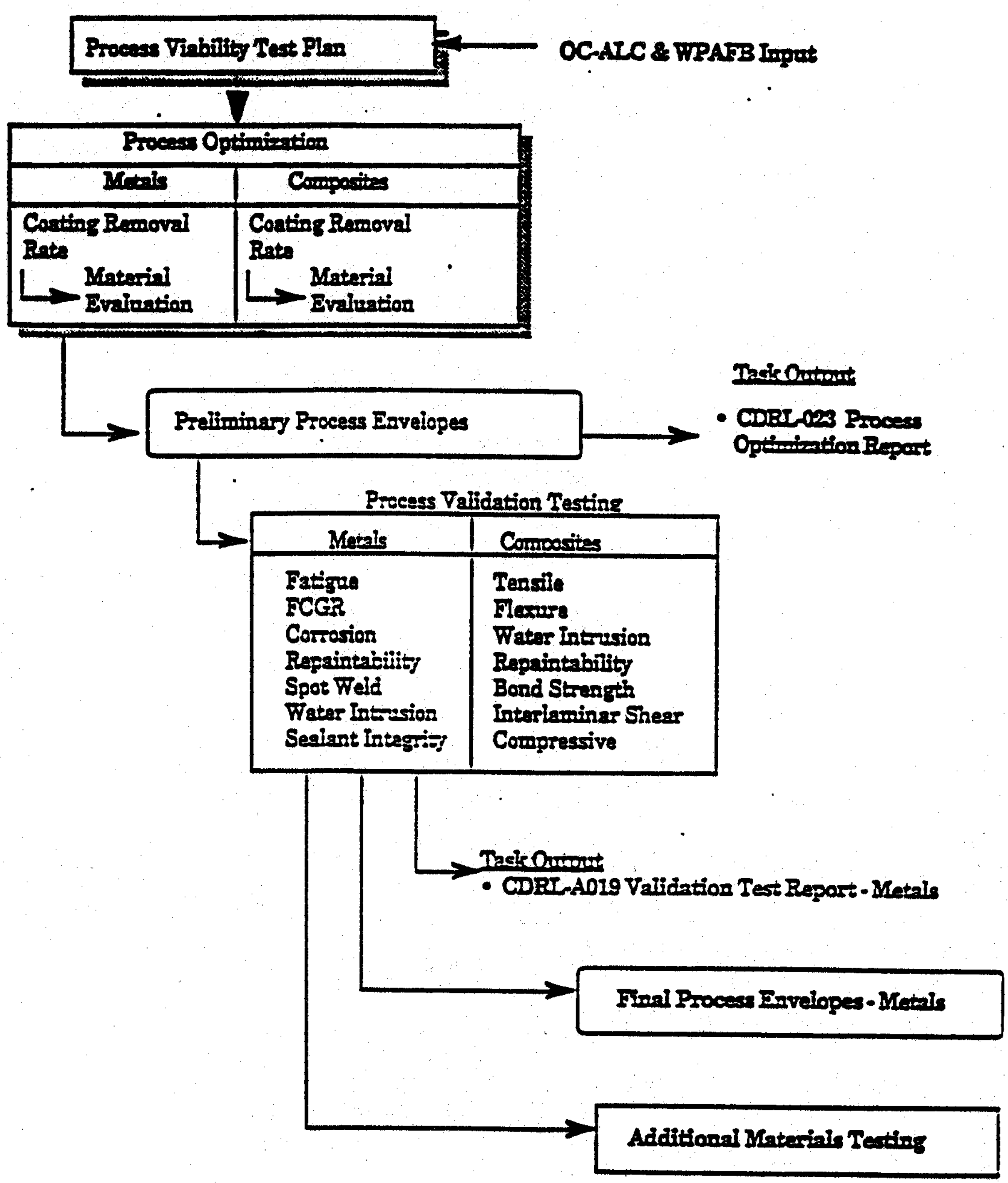


Figure 5. Process optimization/process validation testing roadmap.

2.2.1 Metals.

2.2.1.1 The substrates included 2024-T3 clad, 2024-T3 bare aluminum, 7075-T6 clad, and 7075-T6 bare aluminum. The following paragraphs give certification criteria and manufacturer for these metals. Trace-ability was maintained and a metalluragical report was available by lot numbers for the metals.

2.2.1.2 The 2024-T3 clad was certified per Federal Specification QQ-A-250/5. Coupons were cut from sheet stock with a nominal thickness of 0.032-inch from Reynolds Aluminum.

2.2.1.3 The 2024-T3 bare aluminum was certified per QQ-A-250/4. Coupons were cut from sheet stock with a nominal thickness of 0.032-inch from Reynolds Aluminum.

2.2.1.4 The 7075-T6 clad was certified per QQ-A-250/13. Coupons were cut from sheet stock with a nominal thickness of 0.032-inch from Alcoa Aluminum.

2.2.1.5 The 7075-T6 bare aluminum was certified per QQ-A-250/12. Coupons were cut from sheet stock with a nominal thickness of 0.032-inch from Alcoa Aluminum.

2.2.2 Coating Systems.

2.2.2.1 The coatings for process characterization included Koroflex primer and polyurethane paint (MIL-C-83286). For trace-ability for the material, lot and batch numbers were maintained.

2.2.2.2 The Koroflex primer was certified to TT-P-2760 Type I, Class 1 and was furnished by DeSoto Aerospace Coatings, Inc.

2.2.2.3 The polyurethane topcoat was certified to MIL-C-83286. The coating system was furnished in two components. DeSoto Aerospace Coatings, Inc., furnished Part 1 under Part Number 822X339 and Part 2 under Part Number 910X376.

2.2.3 Surface Preparation Materials.

2.2.3.1 The surface preparation materials included the alkaline detergent, acid etch, and chromate conversion coating. The following paragraphs describe these materials.

2.2.3.2 The alkaline detergent, TURCO Part Number 23, was certified to MIL-C-87936, Type I.

2.2.3.3 The acid etch TURCO Part Number 3003, was certified to MIL-C-38334.

2.2.3.4 The chromate conversion coating was certified to MIL-C-81706 and it was furnished by TURCO under the product name of Accelagold.

2.2.4 The chemical stripper used was TURCO 5351, which was identified by OC-ALC and documented in T.O. 1-1-8.

2.2.5 High-pressure waterjet blasting was done in the automation and coatings facility (ACF), located on the USBI Company campus in Huntsville, AL. The facility became operational in late 1989. Its equipment includes a Niko and a Cincinnati Milcron gantry robot, high-pressure waterjet systems, a water reclamation system, and all associated software. USBI conducts state-of-the-art initial proof-of-process development in this facility, including end effector, sensor, and control experimentation, to gather real-time data on existing and advanced systems. The LARPS process validation was conducted in the Cincinnati Milacron robot cell.

2.2.6 Coupon preparation, testing procedures, and test results were generated during process characterization for the following tests.

- **fatigue - unnotched 100,000 cycles**
- **fatigue - unnotched 500,000 cycles**
- **fatigue - notch front 100,000 cycles**
- **fatigue - notch back 100,000 cycles**
- **FCGR**
- **salt fog corrosion**
- **sealant integrity**
- **repaintability**
- **water intrusion**
- **spot weld integrity**

SECTION III - SM-ALC TEST PROCEDURES AND PRACTICES

3.1 TEST SPECIMENS

The standard fatigue specimen shown in Figure 6 conforms to American Society for Testing Materials (ASTM) E466, Conducting Constant Amplitude Axial Fatigue Tests of Metalic Materials. The FCGR specimen shown in Figure 7 conforms to ASTM E647, Standard Test Methods for Measurement of Fatigue Crack Growth Rates. The Almen type specimen conforms to the Military Standard for Shot Peening, MIL-S-13165. The notch is pressed in with a machined chisel point. This is not a standard specimen, but was developed at OC-ALC on another paint removal evaluation program and was included in this program at the direction of OC-ALC. It has been designated as PMB Test 8T0845 OC-ALC Fatigue Test Surface Flaw (notched specimen).

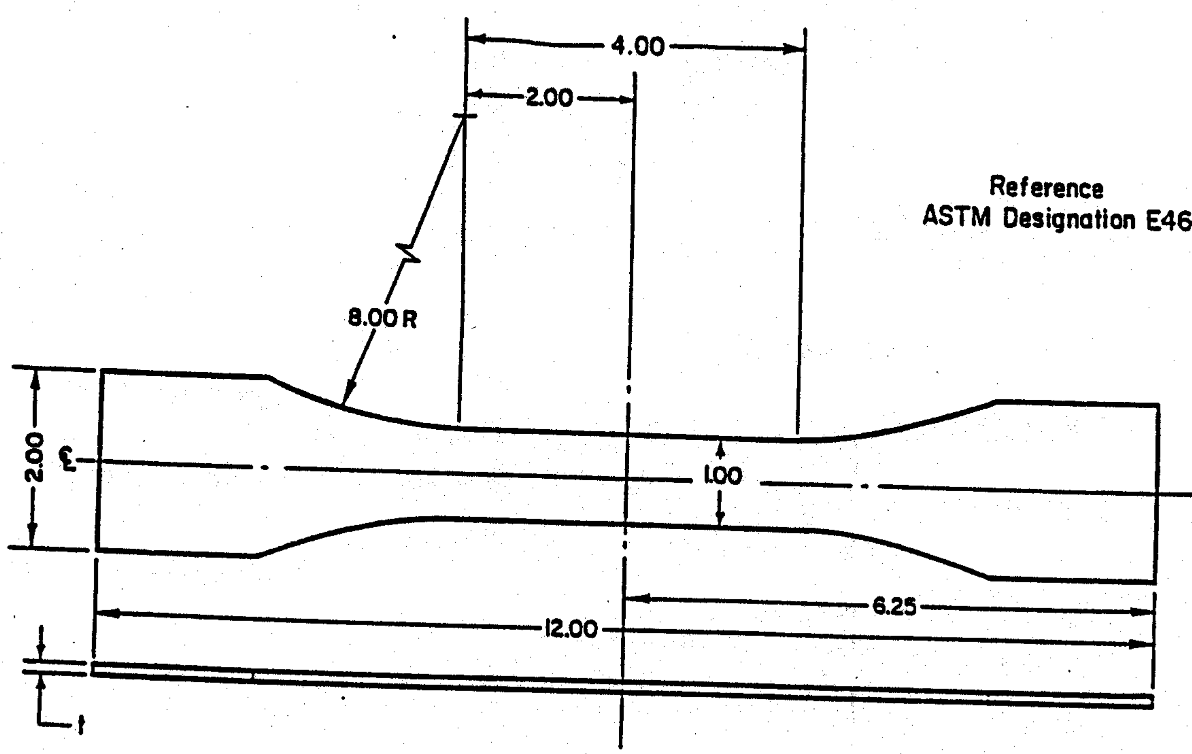


Figure 6. Standard (unnotched) Fatigue specimen.

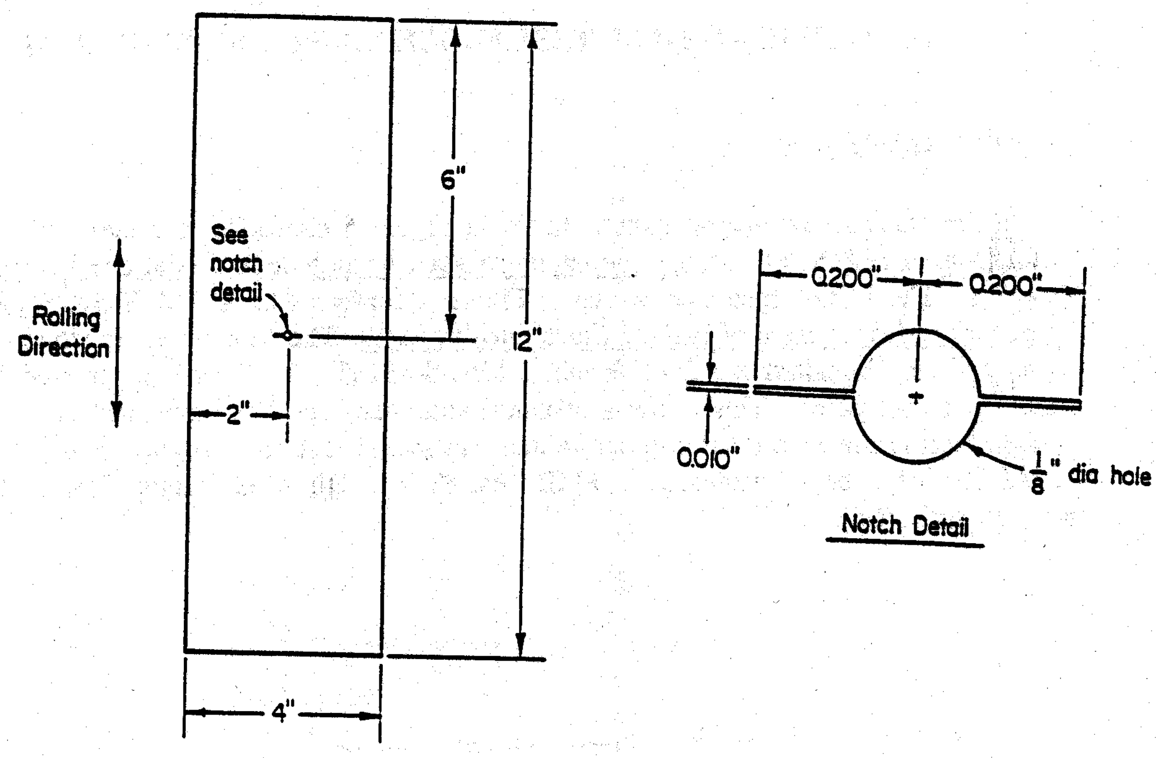


Figure 7. Crack growth specimen.

3.2 EXPERIMENTAL PROCEDURES

3.2.1 Test materials for this study consisted of 2024-T3 and 7075-T6 bare and clad aluminum alloys with a nominal thickness of 0.032-inch. Battelle prepared and painted all test panels for both phases of the study to the following standards:

Step	**Description**
1	**Alkaline detergent cleaned using MIL-C-25769 material.**
2	**Deoxidized using MIL-C-38334 material.**
3	**Within four hours a chemical conversion treatment using material conforming to MIL-C-81706 and applied according to MIL-C-5541 was completed.**

4 Epoxy primer conforming to MIL-P-23377 was applied to a dry film thickness of 0.0006 to 0.0009 inch.

5 A polyurethane topcoat conforming to MIL-C-83286 was applied to a dry film thickness of 0.0017 to 0.0023 inch.

3.2.2 The painting procedures were followed by a 7-day air cure in a controlled laboratory environment, maintained at 72° F and 50 percent relative humidity. Artificial (accelerated) aging was then accomplished by curing the test panels in an oven at 210° F for 96 hours.

3.2.3 The water blasting paint removal test facility was created by draining the immersion ultrasonic facility's immersion tank and placing a painted test panel in a holding fixture at the bottom of the drained tank. The test nozzle was attached to the XYZ stage of the inspection equipment. The stage was then rastered in the XY plane while the nozzle was operating, precisely controlling the traverse rate and coverage pattern while ensuring consistent impingement angle and standoff distance. Transparent safety shields allowed viewing of the process while the built-in drainage system permitted removal and recovery of the resultant paint debris and contaminated water.

3.2.4 For all testing and specimen conditioning, the XYZ positioning system provided translation and control of the test nozzles. The system's probe holder was modified to secure the test nozzles. The multi-axis positioning system was capable of achieving traverse rates greater than 10 inches per second, and it was programmable so that precise velocity profiles could be maintained while traversing a specimen or test panel. The test panel was mounted to a stationary backstop that was on the bottom of the immersion tank. The design of the equipment was such that the nozzle could be translated in an XY fashion. The fixture was adjusted and secured manually to maintain a constant standoff distance (SOD) and impingement angle. This equipment made it possible to condition specimen materials for testing at repeatable parameters.

3.2.5 At the direction of SM-ALC, all baseline fatigue and FCGR materials used for evaluating the candidate stripping processes were treated by applying the alkaline wash and the 96-hour artificial aging process before the individual specimens were machined from parent panels. These baseline material treatments resulted from information derived from the OC-ALC LARPS development program. Tests conducted in the LARPS program revealed the possibility that significant materials effects could be produced in individual machined specimens. Therefore, this treatment of baseline materials was included to avoid biasing the test data.

3.2.6 The same baseline data sets, established at the start of this evaluation (LPW phase), were used for all subsequent analyses for notched fatigue, standard fatigue, and FCGR tests. No new baseline tests were conducted for any of the several assessments. This procedure ensured all of the test materials were drawn from the same material lot(s).

3.2.7 All fatigue tests were conducted with specific cyclic load test frames dedicated to a given alloy type. This means that baseline and experimental specimens were tested on the same frame, slowing the testing process somewhat but ensured more consistent FCGR test results.

3.2.8 It was unnecessary to conduct anything other than macroscopic observations of the fracture surfaces on the baseline notched specimens since all specimens showed cracks that began at the machined flaw. To determine if the crack was caused by fatigue or some artificial variable macroscopic examinations were also conducted on all other fatigue specimens to routinely characterize the crack initiation site.

3.2.9 Fatigue and FCGR specimens were conditioned by applying the paint softener and leaving it on the panels for 5 to 7 hours, then blasting four cycles at the parameters established for each process as described in paragraph 3.5, "Process Characterization." In addition, conditioning was done with the MPW fan nozzle by blasting the specimen with the flow and traverse of the blast stream held perpendicular to the specimen's material roll direction.

3.2.10 Deviations in the conformance of materials used in testing the MPW fan nozzle were documented. In this test the paint softener was not functioning adequately to soften the paint for removal from the test panel. The only variances noted for this segment of the study were that the panels were prepared in the same manner as the others but with a different topcoat color. A different batch of paint softener was used, because the original batch had been depleted through previous testing, and the ambient temperatures were lower.

3.2.11 It was too far beyond the scope of this study to determine which of the above variances could significantly effect the chemical softener's performance when compared with earlier test results. Therefore, it was decided to apply the softener to the unpainted surface and blast that surface. Except for the application of the coatings system, the unpainted surface received the same treatment as the painted surface.

3.2.12 Later, a mistake in the SOD was discovered for this phase of conditioning (conditioned at 8 inches versus 2 inches). Battelle recommended and SM-ALC approved the use of tests conducted concurrently by Warner Robins Air Logistics Center (WR-ALC), Robins AFB, GA, with a similar system at an SOD equal to 2 inches. The WR-ALC testing was more conservative because WR-ALC used bicarbonate of soda as an abrasive agent.

3.2.13 Also, an exception to these procedures is that SM-ALC used it's own procedures to chemically strip some of the panels from this lot.

3.3 TEST EQUIPMENT

3.3.1 Equipment used for paint removal consisted of a waterjet system currently in use at SM-ALC for the LPW paint removal evaluation. This equipment attained 6,500 to 7,000 psi using a nozzle made by WOMA and 7,000 to 8,000 psi using a nozzle made by Stoneage.

3.3.2 For the MPW study, a model D-44 Diesel Engine Aqua Miser® manufactured by Carolina Equipment and Supply Company and a focused fan jet nozzle were used for paint removal. Additional paint removal was accomplished using a single-orifice rotating nozzle from Carolina Equipment. Both nozzles operated at a nominal pressure of 15,000 psi.

3.3.3 For paint stripping trials and specimen conditioning, panels were fastened in a fixture with solid backing. An XY positioning system, normally used for ultrasonic inspection of large parts was used to move the various nozzles over the stationary panel. The nozzles were fastened to the vertical axis of the positioning system so that constant standoff distances could be maintained. The nozzles were assembled so blast stream impingement angles could also be controlled.

3.4 PRODUCTION EFFICIENCY

3.4.1 Initially, the painted panels (2 ft x 2 ft) were divided (by taping) into quarters and a different softener was applied to each quarter. These softeners were TURCO 6813, Fine Organic FO-630 and CB-1058, and Eldorado SR125A (benzyl alcohol). Two nozzles, the WOMA nozzle and a Stoneage RJV2 (a two orifice rotating nozzle), were also evaluated at various standoff distances and traverse rates on the test panels. Dwell times of the various softeners also were evaluated. The pressure of the LPW equipment, which was not consistent, varied with the two nozzles. This affected the rotational velocity of the nozzles. The RJV2 nozzle produced approximately 800 revolutions per minute (rpm) at 6,000 - 8,000 psi.

3.4.2 The epoxy primer/polyurethane topcoat was selected as the standard for stripping efficiency. The TURCO 6813 and Eldorado SR125A essentially were equal as far as softening capability. The SR125A was selected for full evaluation, although it appeared to be somewhat inconsistent in the dwell time required for adequate paint softening. In some panels and at some times the paint "crinkled" in 4 to 8 hours over the entire swath and at other times it crinkled only in spots.

3.4.3 The RJV2 nozzle was the most efficient. After the softener's 4 to 8 hour dwell time, the nozzle removed about 98 percent of the paint and primer from panels at a traverse rate of 5 inches per second at a 5-inch SOD. The cleaned surface was about 4 inches wide. This is a stripping rate of about 8 ft^2/min. The WOMA nozzle was less efficient and substantially noisier during operation than the RJV2 based process. To attain reasonable paint removal, the traverse rate was 3 inches per second at a standoff of 2 inches for a swath of about 3 ¼ inches. This performance equals 0.4 ft^2/minute.

3.4.4 The LPW phase specimens were conditioned at the rates mentioned above with the RJV2 nozzle.

3.4.5 For the MPW study, the Carolina Equipment Aqua Miser® and the 15-degree fan nozzle were used with the SR125A softener. For the same paint system and softener dwell time, the most efficient performance obtained was with a traverse rate of 4 inches/second at a 2-inch SOD, an impingement angle of 60 degrees, and a stripping width of about 2 inches. This is a stripping rate of about 3 ft^2/minute. The softener was extremely inconsistent during these trials.

3.4.6 It was also discovered that if 10 to 15 minutes elapsed between one stripping transverse and the next (adjoining), the first transverse essentially removed the softener from adjoining areas by the blow-by of the blast stream. The performance of the paint removal process on those areas suggested that the softener had been rendered inert.

3.4.7 Cursory assessment was also made of a single jet rotating nozzle designed and manufactured by Carolina Equipment. For the standard paint system, panels were processed at a traverse rate of 5 inches per second and a standoff of 12 inches with a strip width of 4 inches (about the same stripping rate as the RJV2 nozzle). The polysulfide primer and polyurethane topcoat system could be stripped at a traverse rate of 10 inches per second, or approximately double the strip rate of the LPW/RJV2 process. This nozzle, which was not fully evaluated due to the scope of this phase of the study, may warrant further evaluation in a later phase.

3.5 PROCESS CHARACTERIZATION - TEST PARAMETERS

3.5.1 Introduction.

3.5.1.1 Because the nature of any blast type paint removal process is to damage the coating system while removing the coating, the potential exist for such a process to impart blast-related damage to the substrate. The initial development step (optimization) of this program tracked qualitative damage as an index to guide the optimization process. This task is the subsequent step to that development, which entails a much more thorough assessment of possible substrate damage. This step is quite significant in that a process being considered for DOD validation must not damage the substrate.

3.5.1.2 The damage appraisals that would normally be conducted in this type of program are:

- **Erodes cladding material resulting from multiple applications of the blast process.**
- **Increased surface roughness as a result of the blast process.**
- **Residual stress saturation per blast cycle, per developed process parameters.**

- **Possible changes in the fatigue life characteristics of the tested substrate materials.**

- **Possible increased FCGR attributable to the paint removal process.**

3.5.1.3 Test materials for this study were 2024-T3, 0.032-inch bare and clad aluminum alloy, and 7075-T6, 0.032-inch bare and clad aluminum alloy.

3.5.1.4 The blast parameters used for all specimen conditioning in the materials characterization portion of the program were as follows:

LPW w/Stonage RJV2 Nozzle + Softener

Paint Softener	**=**	**Eldorado SR125A (benzyl alcohol)**
Dwell Time	**=**	**5 hours minimum**
Standoff Distance	**=**	**5 inches**
Impingement Angle	**=**	**90 degrees**
Water Pressure	**=**	**8,000 psi**
Traverse Rate	**=**	**5 inches/second**

and

MPW w/Carolina Equipment Fan Nozzle + Softener

Paint Softener	**=**	**Eldorado SR125A (benzyl alcohol)**
Dwell Time	**=**	**5 hours minimum**
Standoff Distance	**=**	**2 inches**
Impingement Angle	**=**	**90 degrees**
Water Pressure	**=**	**15,000 psi**
Traverse Rate	**=**	**4 inches/second**

The parameters listed above are the process parameters derived by optimization of each process.

3.5.2 Qualitative Damage Assessment.

3.5.2.1 As part of the procedure to optimize the candidate paint stripping processes, an assessment of blast-induced damage was required to be certain that damage criteria would be observed. Potential damage to the thin aluminum substrates was monitored by calculating the change in arc height of test coupons commonly referred to as Almen specimens.

3.5.2.2 The Almen specimens used for the arc height calculations were sheared from 0.032-inch-thick painted aluminum sheets to dimensions of 0.75 x 3 inches. The 3-inch dimension was oriented in the sheet rolling direction. All Almen specimens were sheared from painted panels and were blasted on a common face of the original panel.

3.5.2.3 The procedure used to develop the arc height data included quasi-saturation blasting of the coupons, which was equivalent to four paint removal cycles. The coupons were not repainted between the initial paint removal cycle and subsequent blast cycles. This form of testing represented a worst-case situation that might occur from excessive dwell time during paint removal or the equivalent of the expected paint removal cycle of military aircraft.

3.5.2.4 The arc height coupons were mounted in a test fixture that constrained the coupon at two points along each of the 3-inch sides. The constraint locations were approximately 2 inches apart. The test fixture held up to 10 coupons, which permitted conditioning of multiple coupons at identical parameters.

3.5.2.5 The fixture was mounted to the backstop used for the test panel paint stripping so the blast stream traversed the coupon perpendicular to the rolling direction of the aluminum alloy sheet. The coupons were measured before and after the paint removal process to calculate the change in arc height due to the blast process parameters being studied.

3.5.2.6 The results of these tests revealed very low levels of possible blast-induced residual stresses. The readings at all conditions were considered negligible, i.e., indistinguishable from instrument noise or error. The Almen arc height measuring instrument noise range is approximately ± 0.0001 inch.

3.5.2.7 Visual inspection of these materials and subsequent specimen materials detected no discernible surface damage from either blast process. In fact, these observations showed the chromate conversion coating was still intact following stripping and additional blast cycles. Consequently, it was unnecessary to formally test for cladding erosion, surface roughness, and residual stress saturation.

3.5.3 Fatigue Study.

3.5.3.1 Fatigue specimens were sheared from as-received panels (treated and untreated per SM-ALC) and from painted panels after blasting. All fatigue specimens were machined to final dimensions. Fatigue specimens were oriented with the sheet rolling direction, which corresponded to the 12-inch dimension of the specimen, and was perpendicular to the blast direction when there was a defined sense of blast stream direction. The surface flaws (notch) were made by a tool designed to produce the desired notch geometry (Figure 8) in the specimen's surface. All baseline specimens used for assessing the effects of the paint removal process were alkaline washed and aged at 210° F for 96 hours.

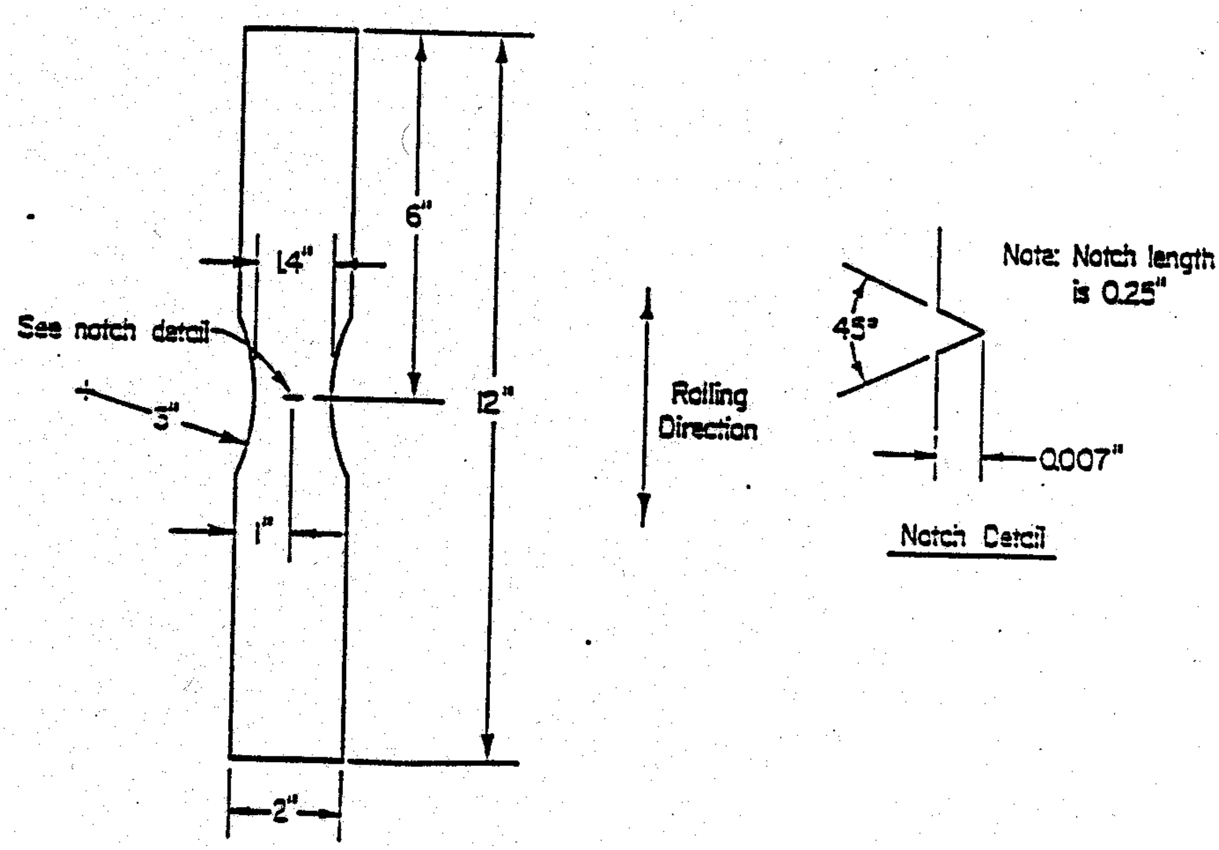


Figure 8. Fatigue life specimen (notched).

3.5.3.2 Notched fatigue specimens were tested following the guidelines of ASTM E466. All fatigue specimens were cycled under load control with a sinusoidal wave form at 10 hertz. Test loads were constant amplitude with a + 0.1 stress ratio. The nominal maximum stress for each material and specimen type was determined by conducting stress versus life cycle (S/N) tests and selecting a maximum stress level that could be expected to result in a material fatigue life of approximately 100,000 fatigue cycles. The maximum stress levels used for each material for both notched and standard baseline and experimental fatigue tests are as follows:

Material	Notched Baseline Maximum Stress, ksi*	Standard Baseline Maximum Stress, ksi*
2024-T3 bare	33.0	50.0
2024-T3 clad	27.5	42.0
7075-T6 bare	30.0	46.0
7075-T6 clad	27.5	35.0

(*ksi = thousands of pounds per square inch)

3.5.3.3 The actual maximum stress levels used for the baseline notched fatigue specimens varied from those predicted by the S/N results. This probably occurred because the process for producing the flaw was not adequately developed, resulting in inconsistencies. The flaws for the baseline and experimental materials were machined at different dates than the specimens used for the S/N tests. In addition, the inability to reproduce the identical flaw geometry led to the subsequent inconsistency of these particular tests (see paragraph 3.6.4.1).

3.5.3.4 Experimental fatigue specimens were conditioned by blasting painted panels previously notched on the front or back surface. Ten fatigue specimens were sheared from each blasted panel. The panels from which specimens were fabricated underwent a total of four blast cycles (one strip cycle + three simulated strip cycles).

3.5.4 FCGR Specimens and Testing.

3.5.4.1 FCGR specimens, with baseline materials treated by OC-ALC, were sheared from as-received panels and from painted panels after blasting. All FCGR specimens were machine finished to final dimensions. A 1/8-inch-diameter hole was drilled through the center of the specimen (test section). An initial 0.040-inch starter notch was then machined by electrical discharge machining (EDM) using a 6 mil traveling wire cut. The sheet rolling direction of all the specimens was oriented with the 12-inch dimension of the specimen, which was normal to the blast direction.

3.5.4.2 FCGR specimens were tested following the guidelines of ASTM E647. All FCGR specimens were cycled under load control with a sinusoidal wave form at 10 hertz. Test loads were constant amplitude with a + 0.1 stress ratio. Crack growth measurements were made with cast epoxy high-temperature Krak® gages.

3.5.4.3 Experimental FCGR specimens were prepared by blasting painted panels. Then twelve specimens were sheared from each of the blasted panels. The panels from which specimens were fabricated underwent a total of four blast cycles (one strip cycle + three simulated strip cycles).

3.6 PROCESS CHARACTERIZATION - TEST RESULTS

3.6.1 Notched Fatigue Life - LPW Jet Nozzle.

The effect of combining chemical softener and water blasting on the substrate's fatigue life was determined by a comparison of the mean fatigue life of the experimental specimens for each notch condition with the mean fatigue life of the baseline specimens. To assess the statistical significance of any changes of fatigue life attributable to the blast processes, the results were analyzed in a student's T-test at a confidence level of 90 percent.

3.6.2 Standard Fatigue Life.

The effect of several paint removal processes (chemical + blasting and chemical) on the substrate's fatigue life was determined by a comparison of the mean fatigue life of the experimental specimens for each process with the mean fatigue life of the baseline specimens. To assess the statistical significance of any changes of fatigue life attributable to the blast processes, the results were analyzed in a student's T-test at a confidence level of 90 percent. A discussion of the results is presented in paragraph 3.6.4.2.

3.6.3 Fatigue Crack Growth Rate.

3.6.3.1 Figures 9 through 16 show curve-fitted representations of the baseline and test sample FCGR data. These figures are log-log plots of crack growth per load cycle (da/dn) as a function of a change in the stress intensity factor (ΔK). Regression analysis was used to develop these curves depicting the baseline and experimental data sets. Each of the data sets was fitted to a cubic quadratic regression model of the form:

$$\log_{10}(da/dn) = a + b\log_{10}(\Delta K) + c\log_{10}(\Delta K^2) + d\log_{10}(\Delta K^3).$$

The correlation coefficient associated with each fit was greater than 0.9, which indicates a good fit (very little scatter in the data).

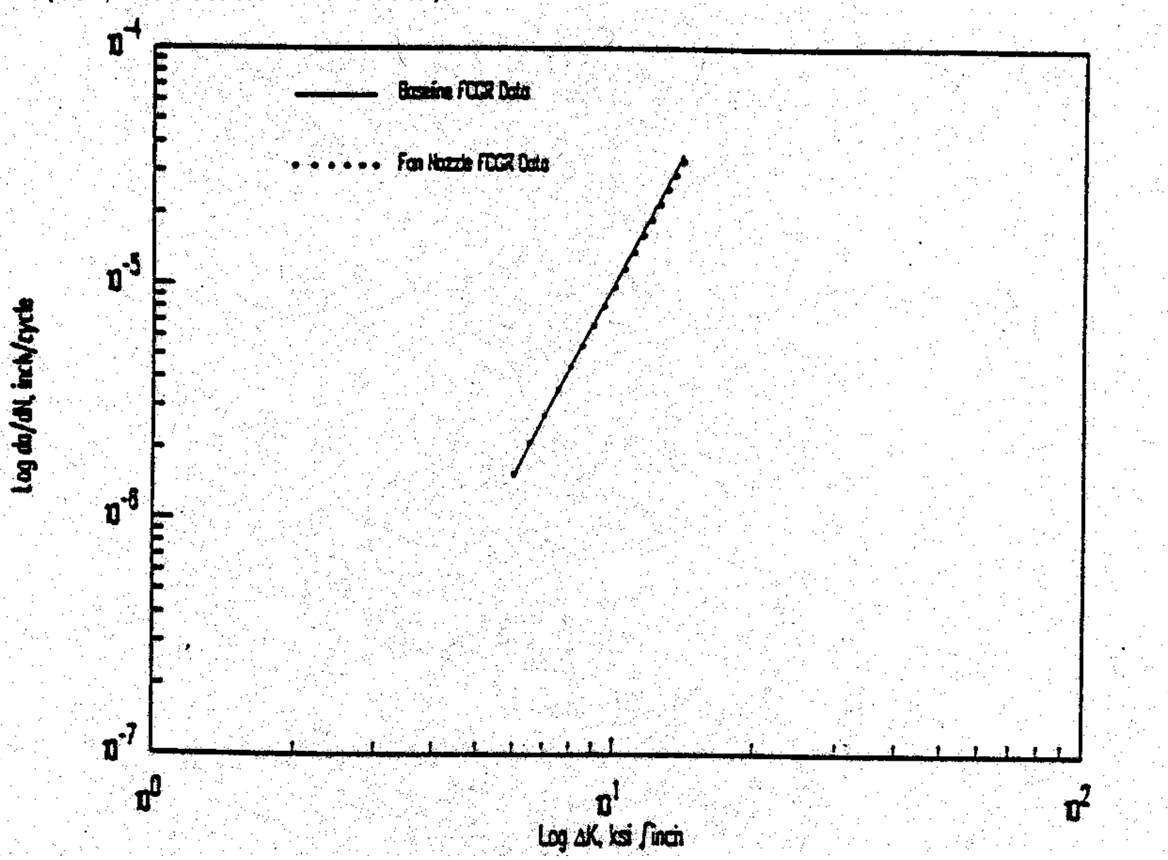


Figure 9. 2024-T3 bare fatigue crack growth rate.

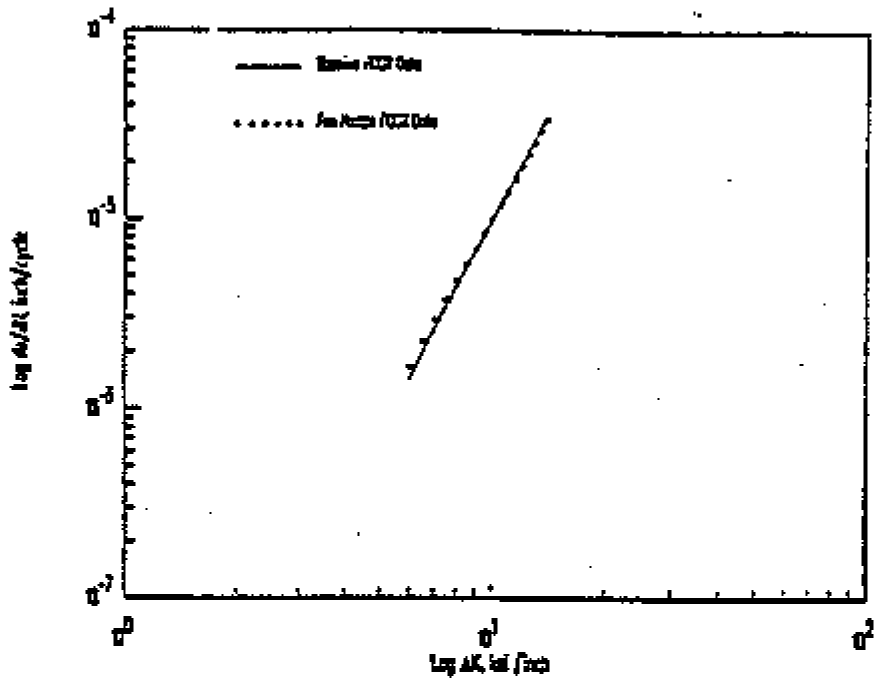


Figure 10. 2024-T3 clad fatigue crack growth rate.

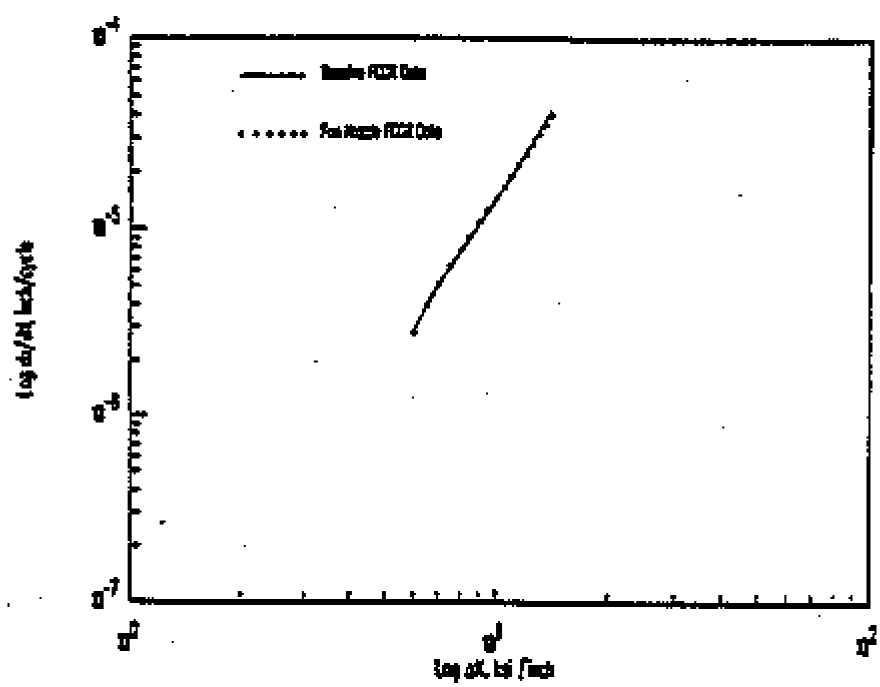


Figure 11. 7075-T6 bare fatigue crack growth rate.

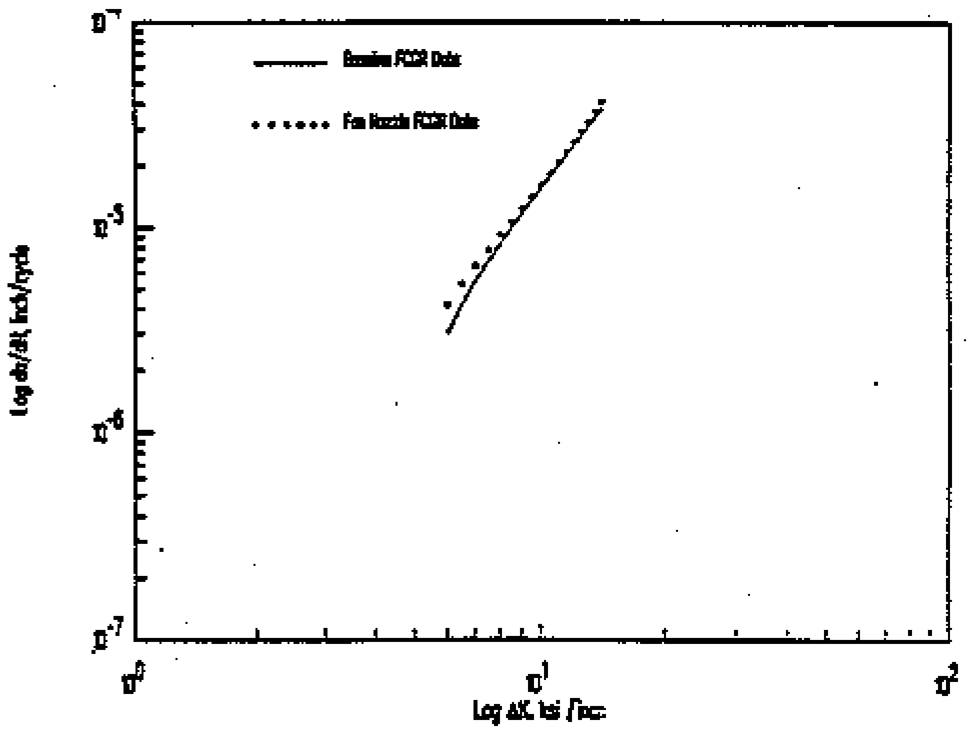


Figure 12. 7075-T6 clad fatigue crack growth rate.

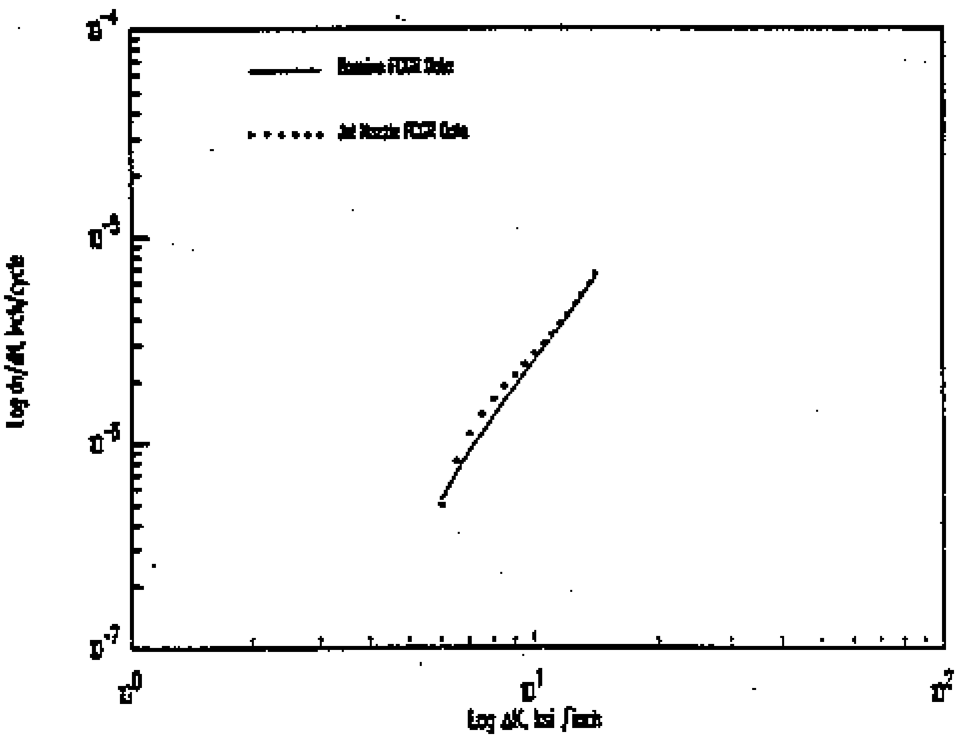


Figure 13. 2024-T3 bare fatigue crack growth rate.

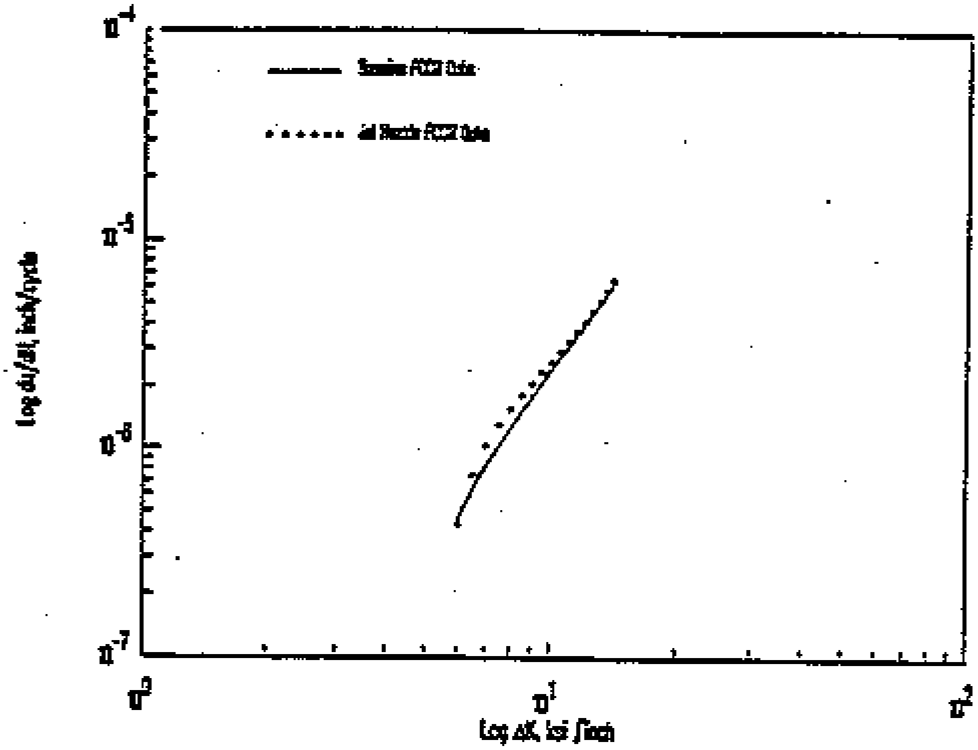


Figure 14. 2024-T3 clad fatigue crack growth rate.

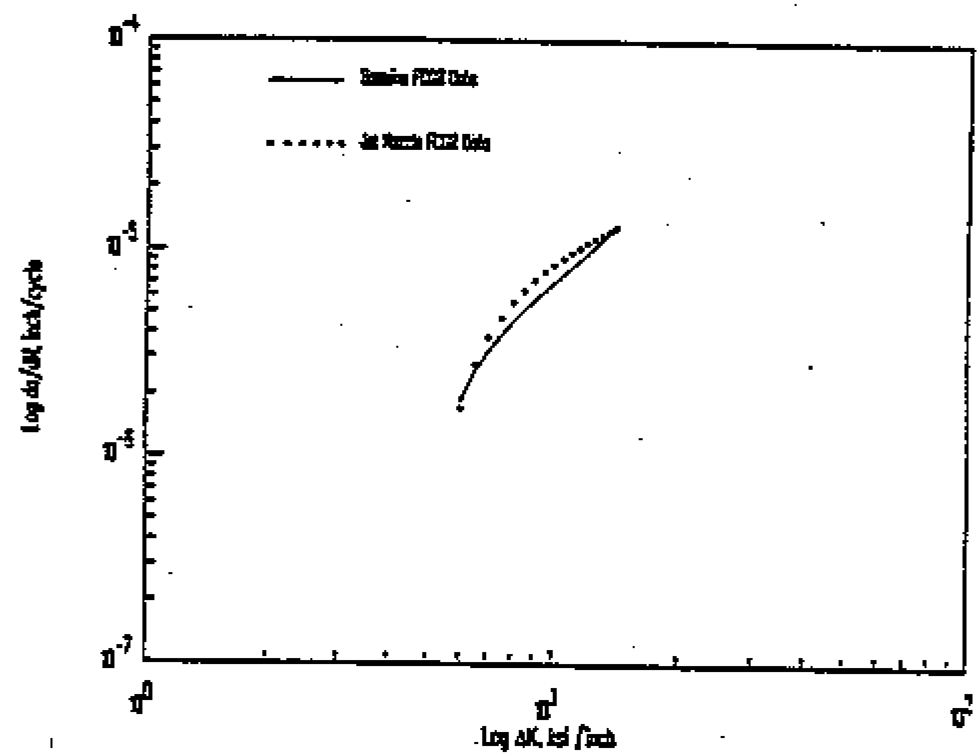


Figure 15. 7075-T6 bare fatigue crack growth rate.

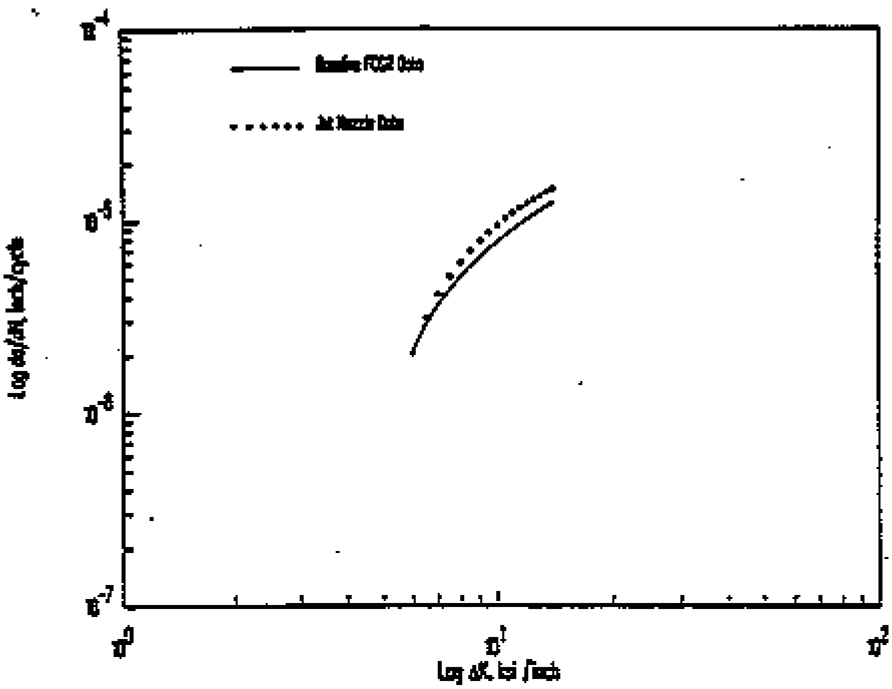


Figure 16. 7075-T6 clad fatigue crack growth rate.

3.6.3.2 The regression fit curves were also used for a quantitative comparison of the baseline and experimental data. Figures 17 through 24 present these data graphically as a percent variation from baseline FCGR. A negative percentage variation corresponds to degraded material resistance to fatigue crack growth or the percent increase in FCGR.

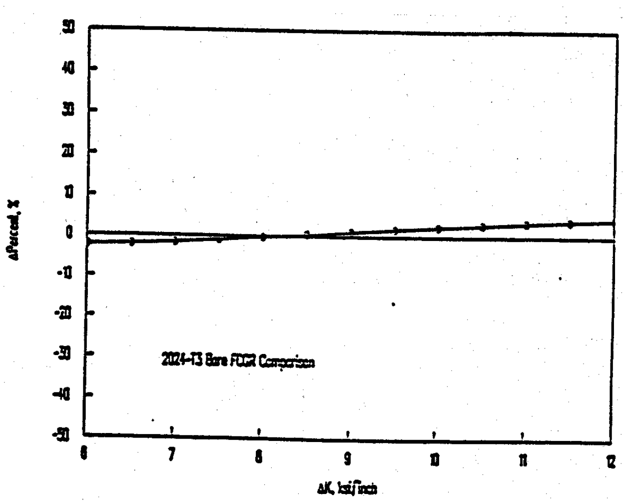


Figure 17. Percent change of FCGR for fan nozzle.

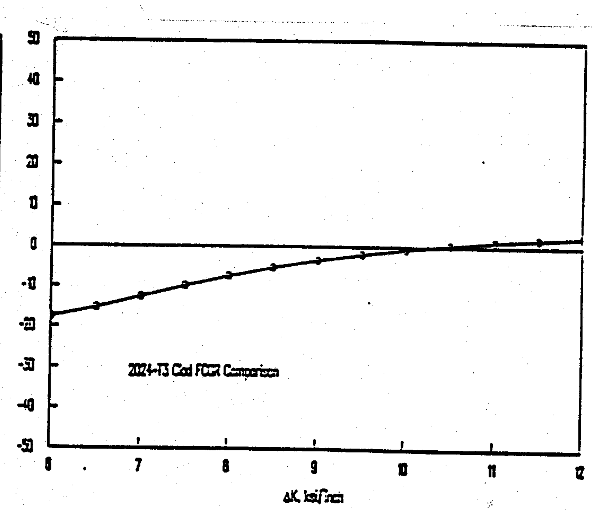


Figure 18. Percent change of FCGR for fan nozzle.

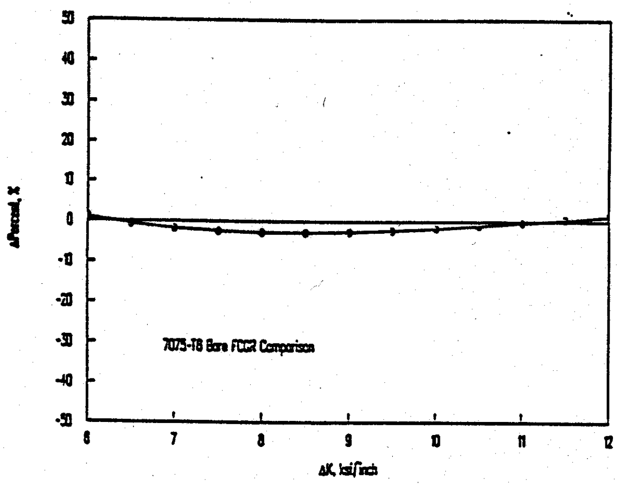


Figure 19. Percent change of FCGR for fan nozzle.

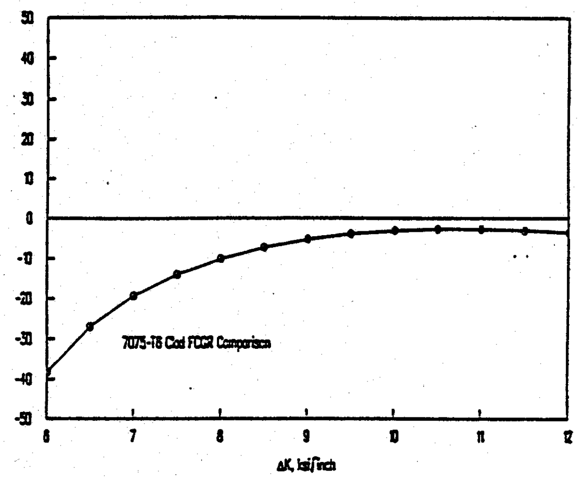


Figure 20. Percent change of FCGR for fan nozzle.

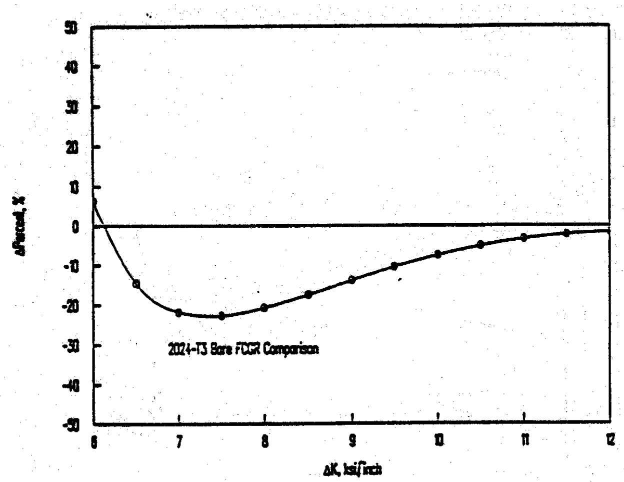


Figure 21. Percent change of FCGR for jet nozzle.

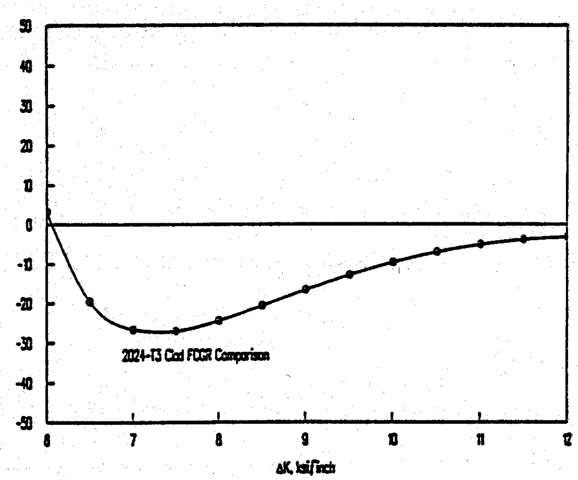
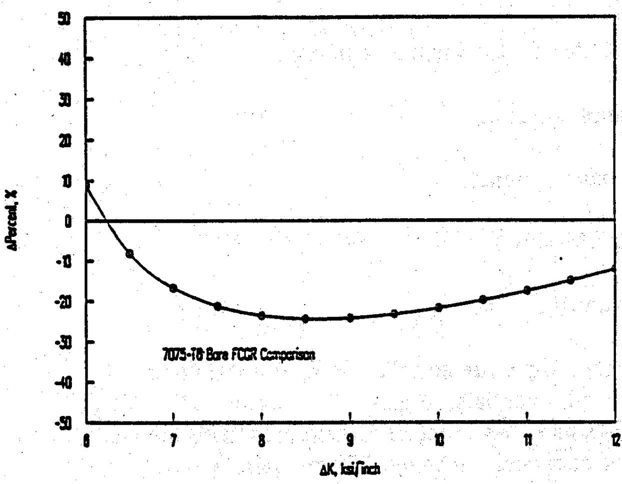


Figure 22. Percent change of FCGR for jet nozzle.



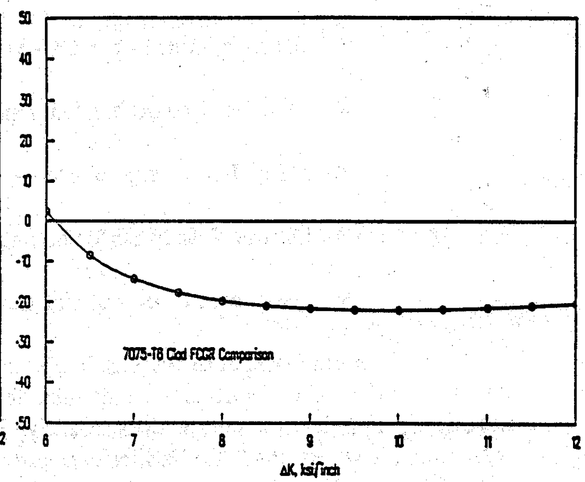


Figure 23. Percent change of FCGR for jet nozzle.

Figure 24. Percent change of FCGR for jet nozzle.

3.6.4 Test Results - Discussions.

3.6.4.1 Fatigue Life - Notched Specimens.

a. The comparison of the baseline notched fatigue data, if taken at face value, shows the LPW jet nozzle process has improved the fatigue life of the materials tested in this project. However, the mean values of the experimental specimens cannot be considered accurate since most of the notched test specimens did not fail. These values represent the number of cycles the specimens had experienced when the test was stopped. Of the specimens that did fail these tests, most of the failures occurred in regions outside of the machined flaw. This showed problems with the fabrication of these specimens, rather than some process effect.

b. Consequently, it was directed that no further testing be conducted with the MPW fan nozzle until the Air Force or another cognizant agency could supply a more reliable test protocol. This is also the reason that the set of back-surface-notched 7075-T6 clad specimens was not tested.

c. In summary, no conclusive information regarding possible process effects on notched fatigue life can be derived from this portion of these evaluations.

3.6.4.2 Fatigue Life - Standard Specimens.

a. Standard fatigue tests were conducted for the following conditions:

- **Baseline (treated per OC-ALC before specimen machining).**
- **LPW Jet Nozzle blasted + paint softener.**
- **MPW Fan Nozzle blasted + paint softener.**
- **Chemical Strip performed by SM-ALC.**
- **As-received (no material treatment).**

b. The comparison of the baseline's mean fatigue life and the LPW jet nozzle data sets indicate statistically significant reductions for all materials, Figures 25 through 28. The magnitude of reduction seen with bare alloys is similar, as is the reduction seen with the clad materials. However, these similarities cause some confusion, since the different fatigue properties of the two alloys could point to evidence of unseen alloy-specific effects.

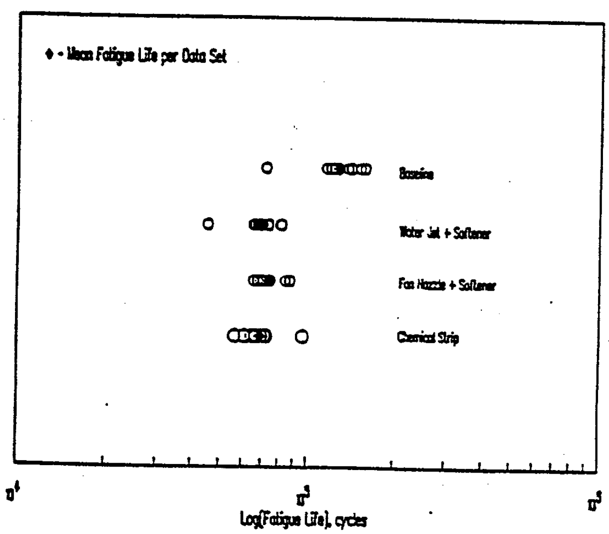


Figure 25. Fatigue data for standard 2024 bare specimens.

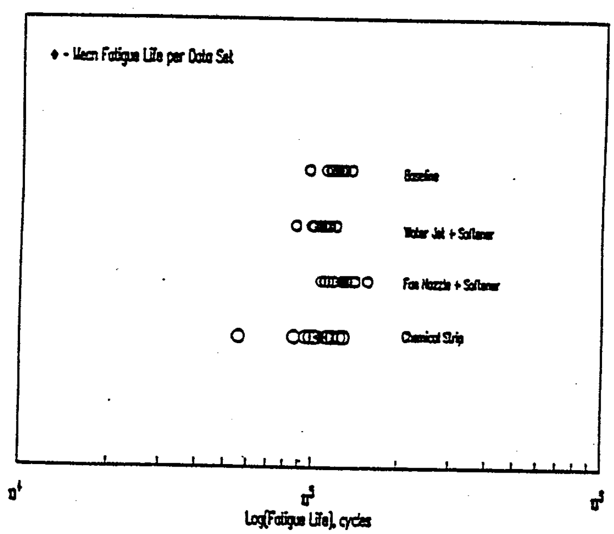
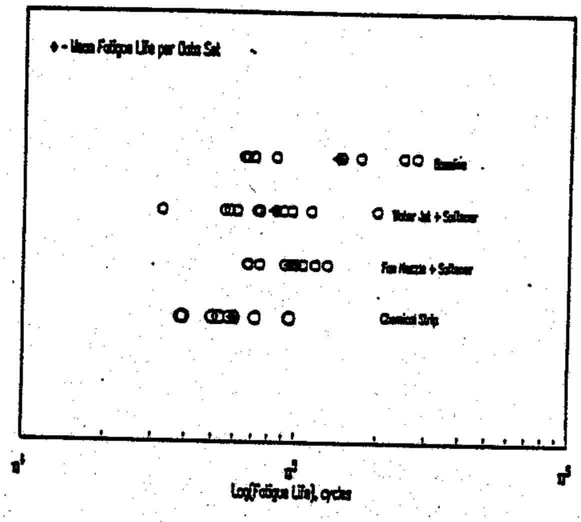


Figure 26. Fatigue data for standard 2024 clad specimens.



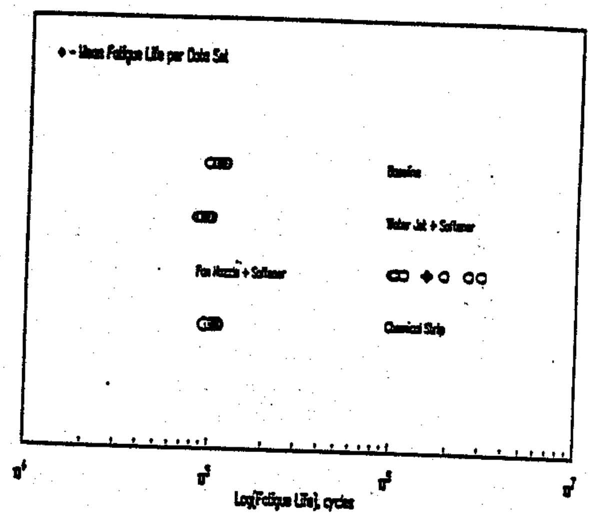


Figure 27. Fatigue data for standard 7075 bare specimens.

Figure 28. Fatigue data for standard 7075 clad specimens.

c. The comparison of the MPW fan nozzle and baseline data sets shows a similar result. In this instance, however, the clad materials exhibited a different response. The 2024-T3 clad data show no change, while the 7075-T6 clad data indicate improved fatigue life expectations. This unexpected improvement was evidently an experimental aberration. The bare materials had similar magnitudes of fatigue life degradation, which were similar to the fatigue life data of bare alloys seen in the MPW jet nozzle study.

d. Figures 25 through 28 show graphical representations for the chemically stripped specimen data. These data showed a similar overall trend. That is, the bare materials exhibited a large reduction of comparable magnitude, while the clad materials showed little or no change. The chemically stripped materials were included in this study to provide additional information and a reference for assessing perceived trends in the standard fatigue data.

e. The results of the chemically stripped specimens do indicate two important concepts. First, the fatigue life reductions probably are due to the water processes. Furthermore, based on work done by San Antonio Air Logistics Center (SA-ALC), Kelly AFB, TX; OC-ALC; and WR-ALC; a fatigue life reduction due to a water-based process is dubious. Second, any effect is more prevalent with the bare materials.

f. Both of these concepts may provide some clues toward identifying a common factor or variable that could account for the fatigue life reduction. One common factor does exist for all the test materials, the sustained presence of the chromate conversion treatment. The coating system's application is another possible variable that should not be ignored, because it was removed by two fundamentally different processes. However, the chemically stripped fatigue data exhibit the same trend, which could indicate that a variable other than the coating system itself had a noticeable effect. To support this hypothesis, the MPW fan nozzle materials were blasted on the unpainted surface, which creates an aspect not common to all of the materials.

g. The chromate conversion coating combined with the artificial aging process possibly could produce a very thin surface layer that, much like an anodize, is harder and more brittle than the underlying substrate. Blast processes that use some type of abrasive tend to remove this coating. While this study did not develop enough categorical data to prove this, the investigation did reveal enough evidence to support the possibility of re-occurrence. Paragraph 3.6.4.3 contains more information on this possibility. This was exhibited as a "mudflat" type surface, containing micro-cracks that could easily act as fatigue crack initiation sites.

h. The test data for as-received materials is informative, but was not originally intended to be included in this study. These tests were conducted before SM-ALC directed Battelle to treat the as-received materials using the OC-ALC method. Tables of fatigue and FCGR data were developed during the SM-ALC test program to compare each material with the baseline data used for the remainder of the study.

i. Statistically significant differences were shown of a magnitude too great to ignore in the respective mean fatigue lives of the specimens, with the exception of the data for 7075-T6 clad tests. This supports the concept that the pre-coating treatment given the materials does effect the fatigue life of most of these alloys.

3.6.4.3 Fatigue Specimen Surface Investigation.

The results of the standard fatigue tests showed a trend of lower fatigue lives for the specimens stripped with benzyl alcohol. The surfaces of various types of specimens including as-received material (baseline), fatigue specimens, and stripped panels were examined in a scanning electron microscope (SEM) to determine if the stripping agent was attacking the aluminum and causing the reduction in fatigue properties. The base materials were 2024-T3 bare, 2024-T3 clad, 7075-T6 bare, and 7075-T6 clad aluminum alloys. For comparison purposes one sample of 7075-T6 bare that had been stripped with methylene chloride was examined, along with three specimens of 2024-T3 bare that had not been treated with a chromate conversion process before painting and stripping. The following paragraphs summarize the results of these examinations.

a. Two as-received baseline specimens were silver because they had not been treated to produce a chromate conversion coating. The typical appearance of the surfaces of these

specimens revealed linear rolling marks from processing the sheet. The orientation of those marks relative to the long axis of the specimens showed one specimen with longitudinal marks (length parallel to the rolling direction) and the other specimen's marks was transverse (length perpendicular to the rolling direction).

b. Chromate conversion coated, painted, and stripped samples' colors ranged from iridescent pink and yellow to dark gold, probably because of variations in the thickness of the chromate conversion coating. This group of nine samples included five tested fatigue samples and four panels that had not been subjected to mechanical testing. The variations in the appearances of the surfaces of all those samples exhibited “mudflat” cracks in the chromate conversion coating. Examination at higher magnifications showed the benzyl alcohol may have slightly attacked the chromate conversion coating.

c. A specimen was stripped with methylene chloride and chromate conversion coated, painted, and stripped with methylene chloride before testing. The specimen showed a mudflat crack pattern in the surface similar to the pattern on the 7075-T6 bare specimen stripped with benzyl alcohol. Comparison of the stripped and non-stripped surfaces on this specimen showed little, if any, effect of the stripping agent on its surface.

d. Several 2024-T3 bare specimens not chromate conversion coated, but painted, then stripped with benzyl alcohol were being tested as part of another program at Battelle. These specimens were also examined and had not been exposed to a chromate conversion treatment before painting and subsequent stripping with benzyl alcohol. They were silver with a hint of a light straw color when rotated under a light.

e. The SEM revealed that the surfaces of these samples appeared to be oxidized but they did not exhibit the mudflat, cracking pattern present on the specimens that had been chromate conversion coated prior to painting. That indicates that chromate conversion produces a film with the mudflat, cracking pattern.

3.6.4.4 FCGR Tests.

a. FCGR testing was done for the LPW jet nozzle + paint softener and MPW fan nozzle + paint softener processes only. The supply of test materials was depleted by the time the chemically stripped specimens were prepared, and no attempt to duplicate this effort with the FCGR tests was considered since a complete set of baseline tests would have been required for a new lot of materials.

b. The FCGR data of the LPW jet nozzle indicated an overall FCGR increase. The magnitudes showed, contrary to the fatigue data, common alloy trends that are dissimilar to other alloy types regardless of alloy condition (bare versus clad). The maximum FCGR increase or decrease is approximately 25 percent and appears or peaks at approximately ΔK = 7 or 8.

c. The FCGR data of the MPW fan nozzle resembles the fatigue data in that there are similar trends based on alloy condition rather than alloy type. However, the FCGR data has reversed the trend in that only the clad materials exhibit any significant FCGR increase. This is manifested only at the lower values of ΔK used in this analysis. The maximum degradations seen are increased FCGR of approximately 20 percent and 40 percent for the 2024-T3 and 7075-T6 clad materials, respectively.

SECTION IV - OC-ALC TEST PROCEDURES AND PRACTICES

4.1 UNNOTCHED FATIGUE TEST

The objective of the unnotched fatigue evaluation was to determine the effects of high-pressure water and chemical stripping on the fatigue life at 100,000 cycles and 500,000 cycles of 2024-T3 clad, 2024-T3 bare aluminum, 7075-T6 clad, and 7075-T6 bare aluminum. Effects were assessed by comparing the fatigue life of processed coupons to the fatigue life of unpainted/as-received coupons. The following paragraphs discuss coupon preparation, processing, and testing procedures for the fatigue evaluation.

4.1.1 Test Coupon Preparation.

4.1.1.1 To maintain coupon trace-ability, a test coupon identification number was mechanically scribed along the 3.5-inch (0.89 m) side of the coupon and below the locating hole. The number was placed on the unprocessed and unpainted side of the coupon. The numbering system followed the scheme below:

Fl-2024C-G#-K#
Fl = fatigue-unnotched
2024C = metal designation = 2024-T3 clad
G# = group number, G1 = 100,000 cycles, G2=500,000 cycles
K# = Koroflex Primer

4.1.1.2 Initially, common coupons were cut for processing and final coupon machining. The procedures applied only to the coupons prepared for the high-pressure waterjet and chemically stripped coupons. The unpainted/as-received coupons were cut directly from the sheet of material and tested. The coupons to be processed were cleaned, coated with a chromate conversion coating and painted as follows:

Step	Description
1	Coupons were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.
2	The surface of the coupons was coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.
3	After drying, coupons were primed with Koroflex primer (DeSoto 823x439), to a dry film thickness of 0.6 - 0.8 mils. All coupons were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.

4 Coupons were air dryed for at least seven days, then aged at 210° F for 96 hours.

4.1.2 Coupon Processing.

4.1.2.1 No processing was required for the baseline coupons. The following paragraphs describe the processing procedures for chemically stripped coupons and high-pressure waterjet coupons.

4.1.2.2 Following artificial aging, the chemically stripped coupons were stripped using TURCO 5351. A uniform coat of the chemical stripper was applied in a light to medium thickness using a non-metallic brush. The chemical stripper was allowed to dwell for 45-60 minutes, but was not allowed to dry on the surface. After the coating had loosened, five passes were made on the surface of the coupon using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool. The surface was rinsed with warm water at 100-120° F to remove the residue. This procedure was repeated for three additional cycles using unpainted/chemically stripped coupons to simulate three additional stripping cycles before testing.

4.1.2.3 The coupons for waterjet processing were subjected to four cycles. The first cycle removed all of the paint. The remaining cycles, which simulated three additional stripping cycles, were performed on unpainted/processed metal. A robotic index of 0.1 inch between cycles was used to simulate robotic inconsistencies. The following set of parameters was used to process the fatigue notch front coupons: 24,000 psi, 1.3-inch standoff, 1.25-inch/second travel rate.

4.1.3 Procedures.

4.1.3.1 Fatigue coupons were fabricated directly from common coupons cut from the as-received sheet of metal. After processing the high-pressure waterjet coupons and chemically stripped coupons, fatigue coupons were fabricated from common coupons. According to Appendix XI, ASTM E466, a radius of approximately 0.01-inch was prepared by hand sanding the specimen's edges, not the blasted surfaces. Figure 29 shows the coupon.

4.1.3.2 After fabrication, all fatigue test coupons were visually inspected at 20X. Cracks or machining marks perpendicular to the length of the coupon were removed by polishing with 300- and 600-grit sandpaper. After polishing, coupons were inspected again at 20X and repolished as required until the defects were removed. One machine was used to evaluate the fatigue behavior of all materials at 100,000 cycles, and another machine was used to evaluate the fatigue behavior of all material at 500,000 cycles. No crossover testing was allowed, since fatigue properties can vary depending on the machine.

4.1.3.3 A baseline stress level for each substrate material was established by determining the maximum stress required for failure at 100,000 cycles, ± 20,000 cycles, using a stress ratio of 0.1 and a frequency of 10 hertz. This maximum stress for each material was then used for all

subsequent tests on coupons processed by high-pressure water and chemicals according to ASTM E466. All data were collected using the automated data acquisition system. Averages, standard deviations, and confidence intervals were calculated. Statistical analyses were used to determine if significant differences existed between the high-pressure water-processed coupons, chemically stripped coupons, and unpainted/as-received coupons.

4.1.3.4 A baseline stress level for each substrate material was established by determining the maximum stress required for failure at 500,000 cycles, ± 100,000 cycles, using a stress ratio of 0.1 and a frequency of 10 hertz. This maximum stress for each material was used for all subsequent tests on coupons processed by high-pressure water and chemicals per ASTM E466. All data was collected using the automated data acquisition system. Data averages, standard deviations, and confidence intervals were calculated. To determine if significant differences existed between the high-pressure-water-processed coupons, chemically stripped coupons, and unpainted/as-received coupons, statistical analyses were

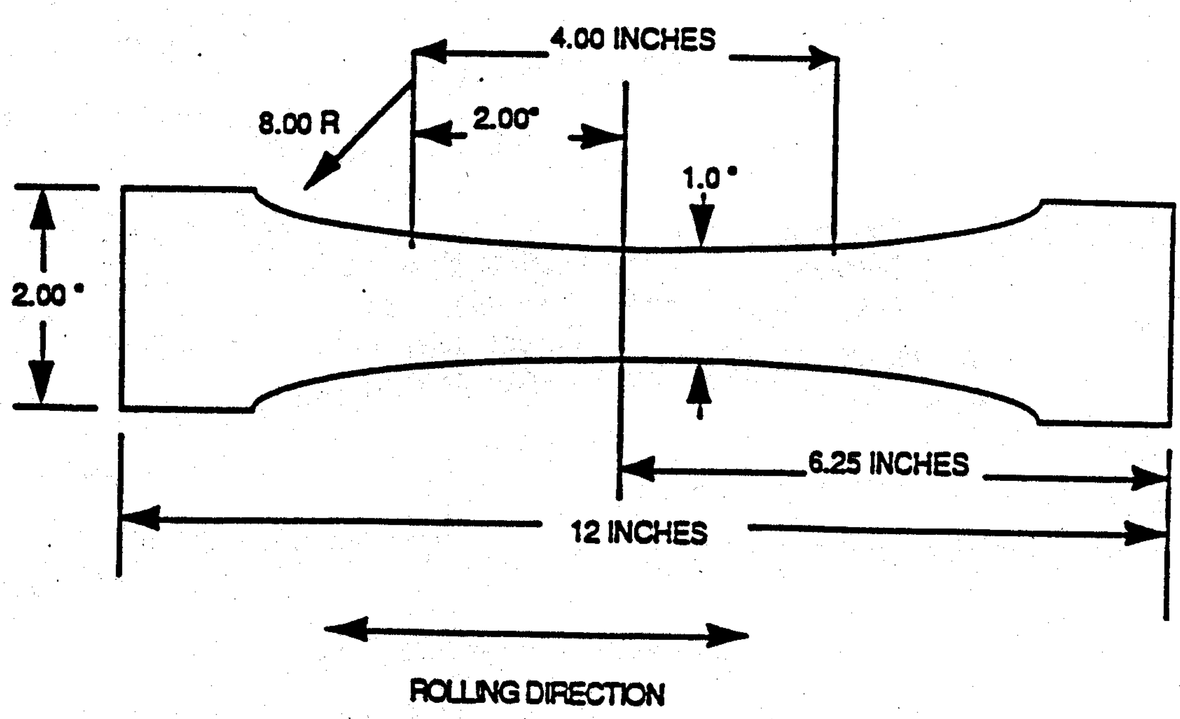


Figure 29. Fatigue life specimen.

4.2 NOTCHED FATIGUE TEST

4.2.1 Notched Front Fatigue Test.

4.2.1.1 The objective of the notched front evaluation was to assess the effects of high-pressure waterjet on the notched fatigue life of 2024-T3 clad, 2024-T3 bare, 7075-T6 clad, and 7075-T6 bare at 100,000 cycles. To validate process effects the high-pressure waterjet process was compared to chemical stripping.

a. The notch front test was developed by OC-ALC as a method to simulate aircraft surface defects such as scratches and corrosion pits to quantify the effects of alternative processes on the fatigue life of "damaged" aircraft skins. From the scope of work defined in CDRL-018-3, three preliminary envelopes identified during process optimization testing were to be used to initially process fatigue notch front coupons of 2024-T3 clad. These coupons would be tested, and a candidate envelope for processing the remainder of the coupons would be selected. Figure 30 shows the initial test approach.

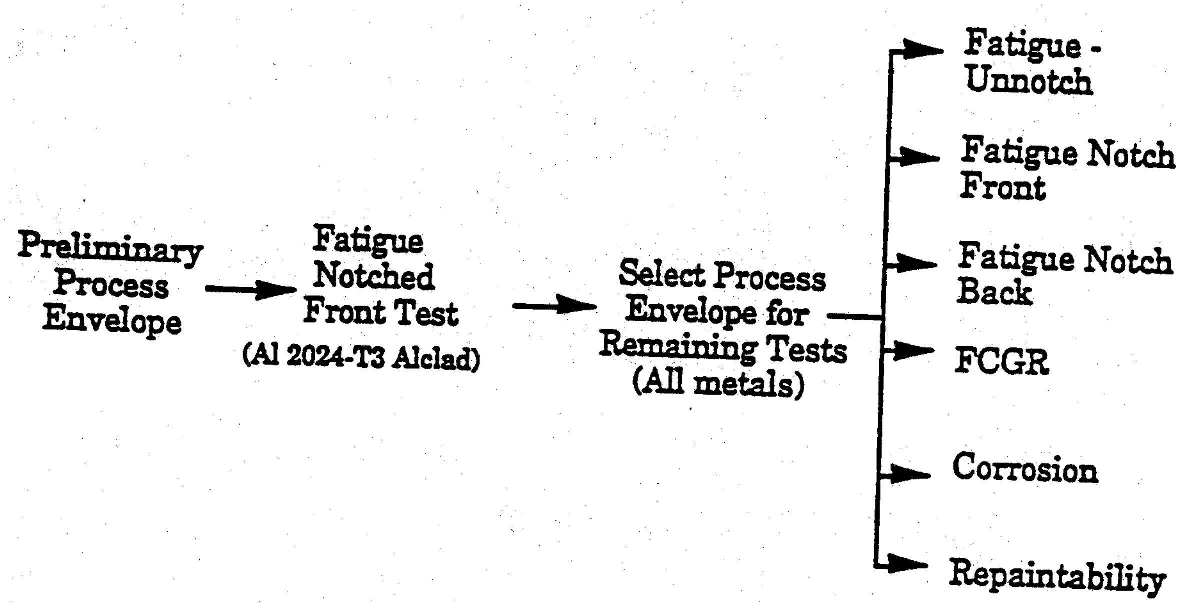


Figure 30. Planned test approach - CDRL-018-3.

b. Results from the initial notched fatigue testing of 2024-T3 clad showed the fatigue life of notch front coupons was being significantly reduced compared to that of the unpainted/as-received coupons. Consequently, the testing was expanded beyond the initial scope of work defined in CDRL-018-3. Also, the test approach shown in Figure 30 was modified to the approach shown in Figure 31 to determine the cause of the reduction. Based on test results from fatigue notch front and back coupons, the reduced fatigue life was attributed to the coupon preparation procedures. As a result, these procedures were modified to better replicate surface preparation and painting.

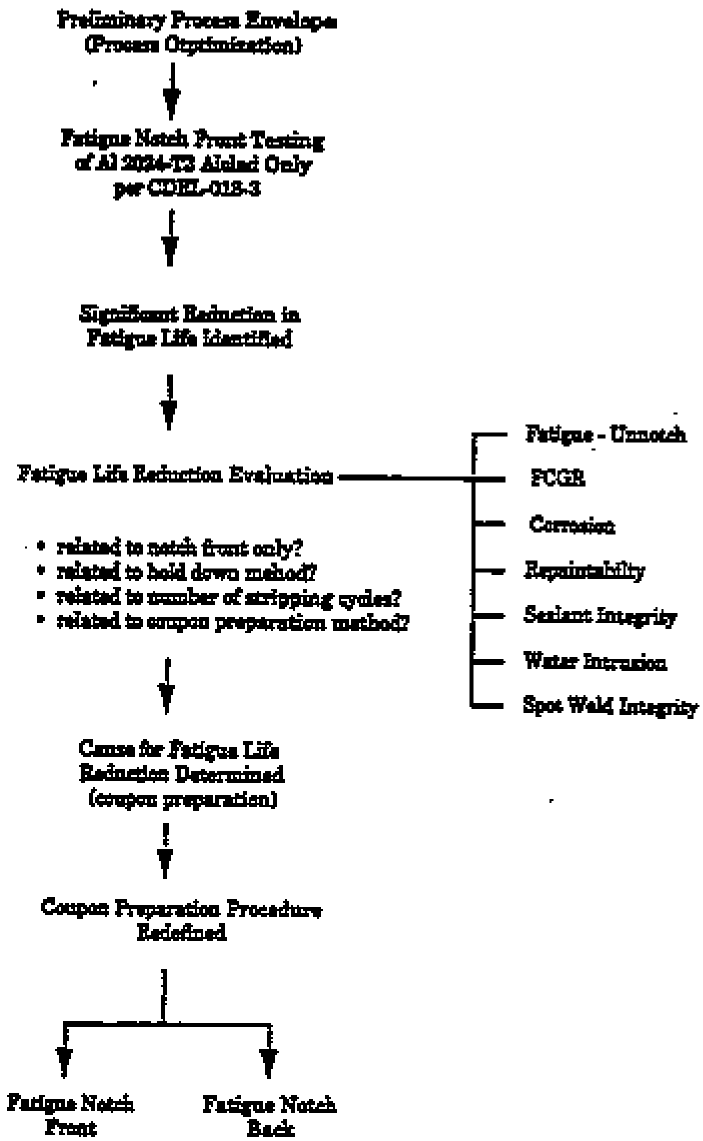


Figure 31. Modified planned test approach to process validation testing.

c. The results from the fatigue notch front tests, based on the redefined coupon preparation procedures, are discussed in this section. Appendix II discusses, in detail, the approach and results of testing to identify the cause for the reduced fatigue life prior to baseline.

4.2.1.2 Test Coupon Preparation.

a. To maintain trace-ability, a test identification number was scribed along the 3.5-inch (0.089-m) side of the coupon and below the locating hole on the unprocessed and unpainted side of the coupon. The following number scheme was used:

F2-2024C-G#-A

F2 = fatigue notch front
2024C = metal designation = 2024-T3 clad
G# = group number, G1 = 100,000 cycles
A = K1 = Koroflex Primer (set 1); K2 = Koroflex Primer (set 2);
E1 = Mil-P-23377 Primer (set 1)

b. Initially, a notched common coupon, cut from an as-received sheet of metal (Figure 32), was prepared. The notch was cut on the side of the coupon to be painted and processed. For the fatigue notch evaluation, the baseline configuration was a painted, chemically stripped coupon. The coupon preparation procedure was defined by OC-ALC to replicate a current painting and chemical stripping process used in production. The procedures for preparing the baseline and high-pressure waterjet coupons are discussed below:

- **Baseline coupons.**

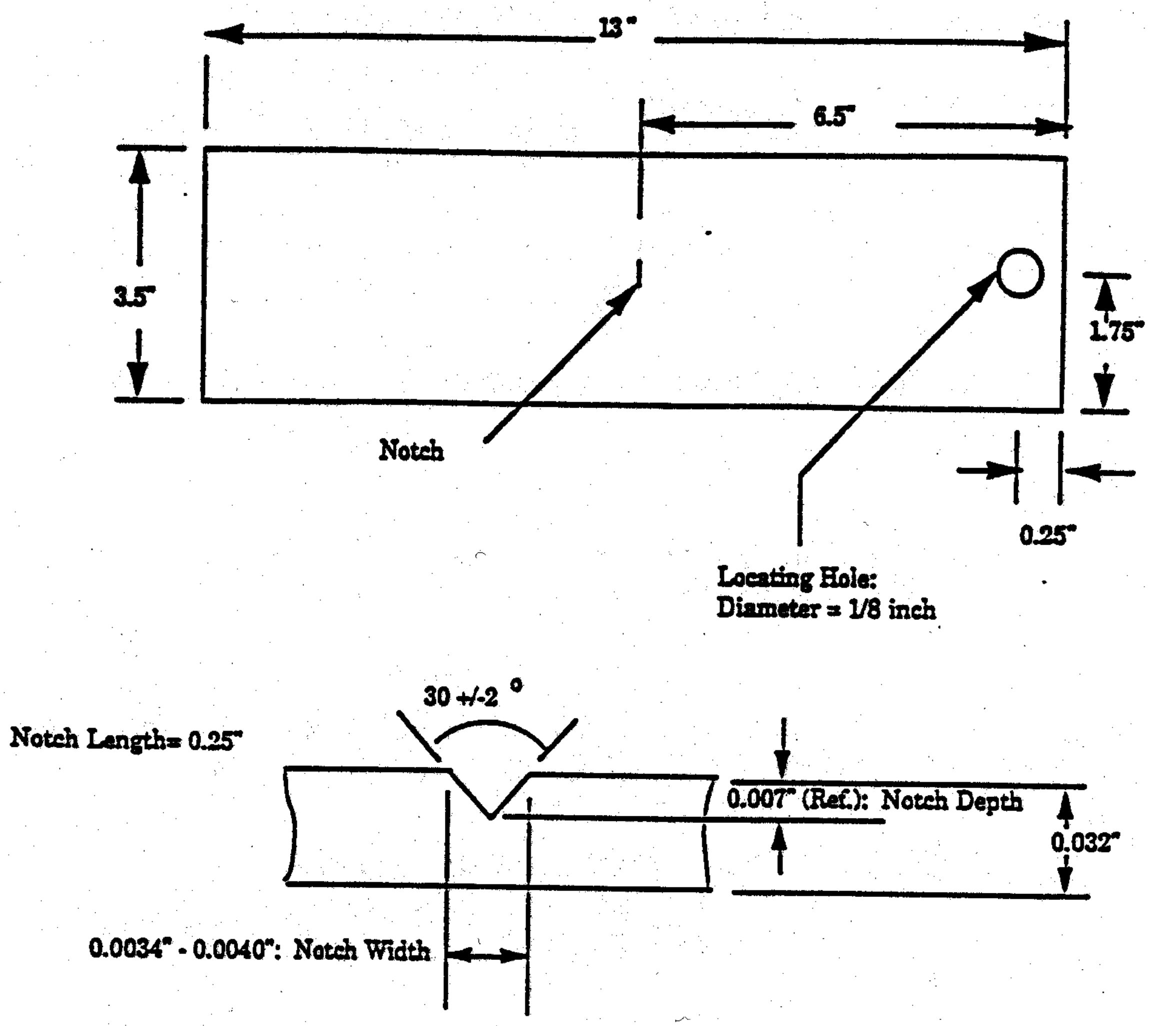
Step	**Description**
1	**Coupons were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.**
2	**The coupon surfaces were coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, coupons were primed with Koroflex primer (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils. All coupons were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Coupons were air dried for at least 7 days, then aged at 210° F for 96 hours.**

5 **Following artificial aging, the coupons were chemically stripped using TURCO 5351 to remove the paint. During the chemical stripping, five passes were made on the surface of the coupon using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool.**

6 **Steps (1)-(5) were repeated, then steps (1)-(4) were repeated a third time. Afterwards, the coupons were available for testing.**

- **High-pressure-waterjet-processed coupons.**

Step	**Description**
1	**Coupons were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.**
2	**Coupon surfaces were coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, coupons were primed with Koroflex primer (DeSoto 823x439), to a dry film thickness of 0.6 - 0.8 mils. All coupons were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Coupons were air dried for at least 7 days, then aged at 210° F for 96 hours.**
5	**Following artificial aging, the coupons were chemically stripped using TURCO 5351 to remove the paint. During the chemical stripping, five passes were made on the surface of the coupon using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool.**
6	**This time steps (1)-(4) were repeated. Following the second artificial aging, the coupons were processed using the high-pressure waterjet and steps (1)-(4) were repeated again. The coupons were then available for testing.**



Notching Procedure

Grind tip of tool steel chisel to 30-deg +/-2-deg

→ Mount chisel on chuck of end mill

→ Mount coupon in end mill

→ Introduce notch to 7 mil depth at center of coupon. Use dial indicator to control depth of penetration

Figure 32. Common coupon for fatigue notch front testing.

4.2.1.3 Coupon Processing.

a. For the fatigue notch evaluation, baseline coupons were painted and chemically stripped. The preparation process is discussed in Paragraph 4.2.3.

b. Coupons of each metal were waterjet stripped using four cycles. The first cycle removed all of the paint. The remaining cycles, which simulated three additional stripping cycles, were performed on unpainted metal. An index of 0.1 inch between cycles was used to simulate robotic inconsistencies. Coupons were held firmly to a back plate, as shown in Figure 33. For notched coupons, the notched and painted sides were blasted. The fatigue notch front coupon stripping parameters were 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate.

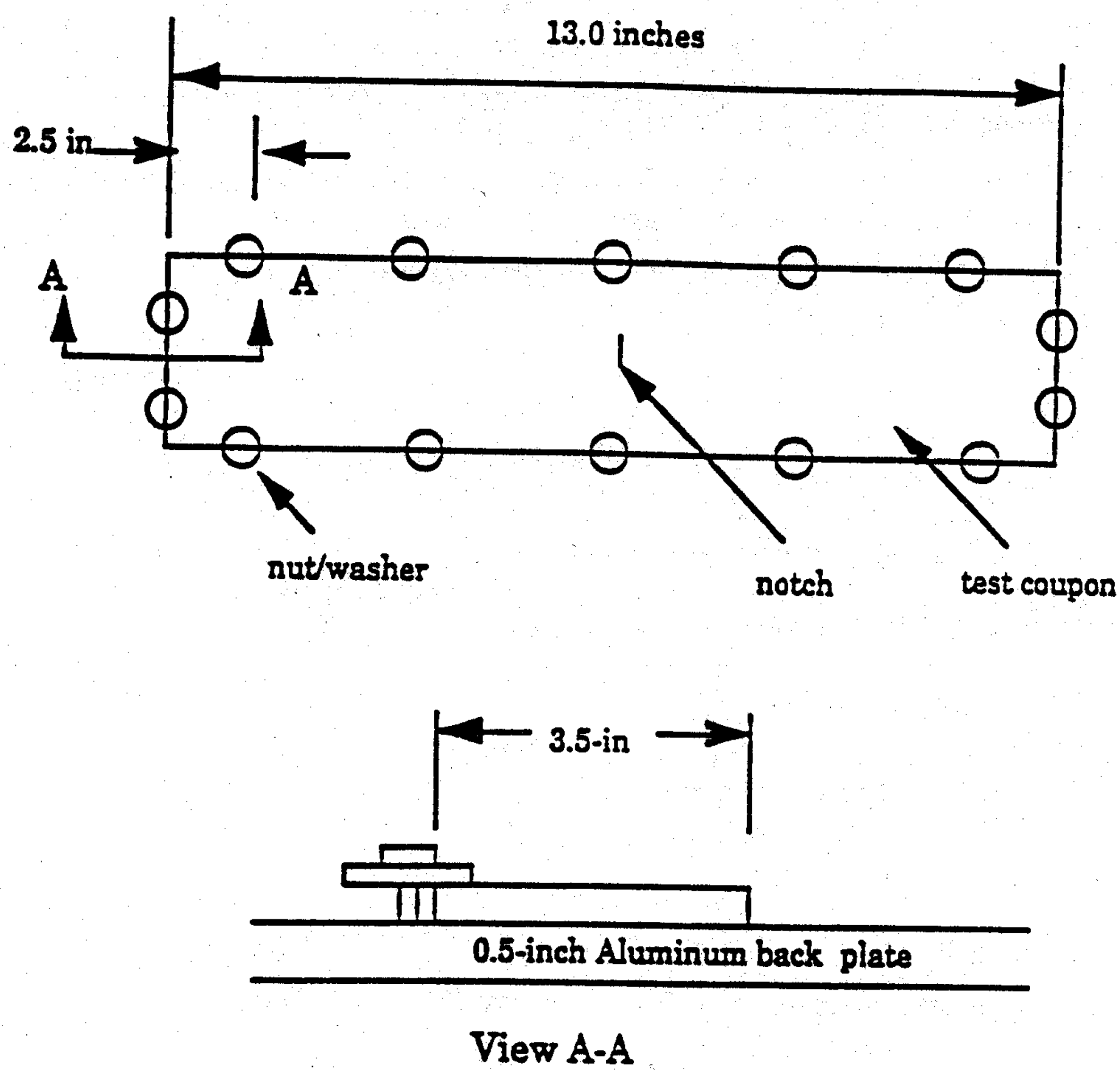


Figure 33. Hold down method for fatigue notch front coupon processing.

4.2.1.4 Procedures.

a. After processing, common coupons were fabricated into fatigue test coupons according to the procedures described in ASTM E466, Appendix XI. Specimen corners in the test region were hand sanded to a radius of approximately 0.010 inch, only on the edges, not the blasted surfaces. Figure 34 shows the fatigue notch front coupon.

b. After fabrication, all baseline coupons were visually inspected at 20X. Cracks or machining marks perpendicular to the length of the coupon, visible at this magnification, were removed by polishing with 300- and 600-grit sandpaper. After polishing, coupons were re-inspected at 20X and repolished as required until the defects were removed. One machine was used to evaluate the fatigue behavior of all material at 100,000 cycles, and another machine was used to evaluate the fatigue behavior of all material at 500,000 cycles. No crossover testing was allowed, since fatigue properties can vary depending on the machine.

c. For each substrate material, the maximum stress required to produce failure at 100,000 cycles, ± 20,000 cycles, using a stress ratio of 0.1 and a cycling frequency of 10 hertz was determined. This maximum stress for each material was used for all subsequent tests of high-pressure waterjet stripped coupons per ASTM E466. All data were collected using the automated data acquisition system. Averages, standard deviations, and confidence intervals were calculated. Statistical analyses determined if significant differences between the baseline (chemically stripped coupons) and high-pressure-waterjet-processed coupons existed.

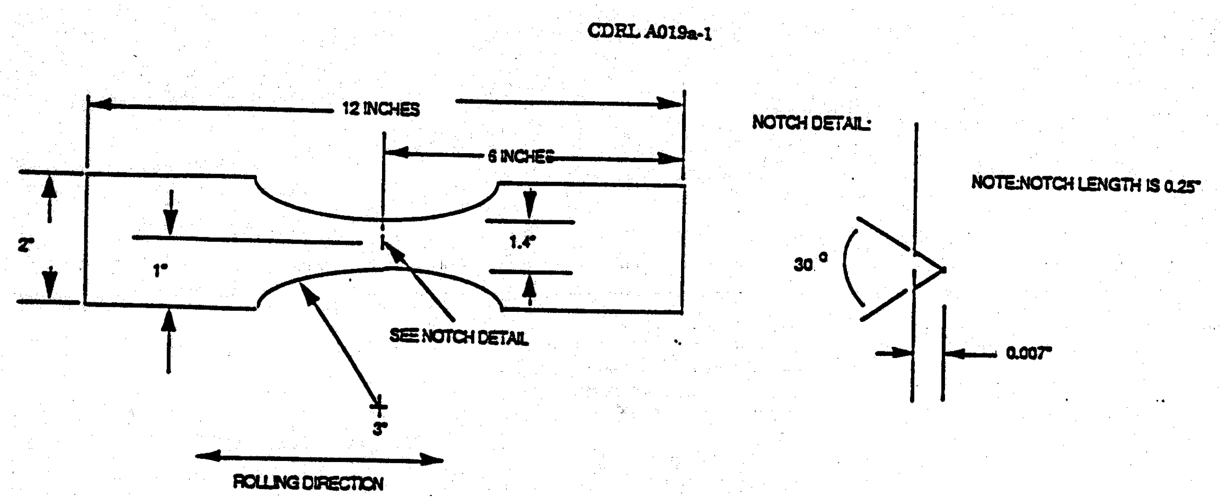


Figure 34. Fatigue notch front test specimen.

4.2.1.5 Notched Front Test Results.

These tests will be performed at a later date using coupons notched by OC-ALC and prepared by USBI.

4.2.2 Notched Back Fatigue Test

4.2.2.1 The objective of the notched back evaluation was to assess the effects of high-pressure water and chemical stripping on the fatigue life of notch back coupons of 2024-T3 bare, 2024-T3 alclad, 7075-T6 bare, and 7075-T6 alclad at 100,000 cycles. To validate process effects the high-pressure waterjet process was compared to chemical stripping.

a. The notch back test was developed as a method to simulate inboard surface defects such as corrosion pits on aircraft to quantify the effects of the alternative paint stripping process on the fatigue life of "damaged" aircraft skins. The initial scope of work defined in CDRL-018-3 was based on using unpainted/as-received coupons as the baseline condition and comparing effects from chemical stripping and high-pressure waterjet process to validate process effects.

b. Test results generated during initial testing showed that the coupon preparation procedures significantly impacted fatigue notch front and fatigue notch back life. Consequently, coupon preparation procedures were redefined to better replicate the current paint stripping and painting procedures at OC-ALC.

4.2.2.2 Test Coupon Preparation.

a. To maintain trace-ability, a test identification number was scribed along the 3.5-inch (0.089-m) side of the coupon and below the locating hole on the unprocessed and unpainted side of the coupon. The numbering system used follows:

F3-2024C-G#-A

F3 = fatigue-notch back
2024C = metal designation = 2024-T3 clad
G# = group number, G1 = 100,000 cycles
A = Koroflex primer

b. Initially, a notched common coupon, cut from an as-received sheet of metal, was prepared. This common coupon was cut on the side of the coupon not to be painted and processed. The preparation procedures for the baseline and high-pressure waterjet coupons are discussed below:

- **The baseline coupons for the fatigue notch back tests were not painted, since these coupons represent inboard surface defects and since chemical stripping**

induces no mechanical stress on the surface. However, thermal treatment was conducted to simulate substrate aging. The common coupons were notched and heated to 99° C for 96 hours. After cooling, the coupons were available for testing.

- **The high-pressure waterjet coupons were painted for the fatigue notch back tests. Since the high-pressure waterjet process is an impingement process, the coupons were painted to better replicate stripping conditions and post process surface conditions. The common coupons were notched as shown in Figure 32, then processed as follows:**

Step	**Description**
1	**The unnotched side of the coupon was cleaned using a detergent conforming to MIL-C-87936 Type I followed by an acid etch using a solution conforming to MIL-C-38334.**
2	**The unnotched surface of the coupon was coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, coupons were primed with Koroflex primer (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils. All coupons were coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Coupons were air dried for at least 7 days.**
5	**Coupons were heated at 99° C for 96 hours.**
6	**After this artificial aging, the coupons were available for high-pressure waterjet blasting.**

4.2.2.3 Coupon Processing.

Coupons of each metal were waterjet blasted for four cycles on the unnotched side. The first cycle removed all of the paint. The remaining cycles, which simulated three additional paint stripping cycles, were performed on unpainted metal. An index of 0.1 inch between cycles was used to simulate robotic inconsistencies. The fatigue notch back coupons were processed using 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate.

4.2.2.4 Notched Back Fatigue Test Procedures.

a. After processing, common coupons were fabricated into fatigue test coupons according to the procedures described in ASTM E466, Appendix XI. Specimen corners in the test region were hand sanded to a radius of approximately 0.010 inch, only on the edges, not the blasted surfaces.

b. After fabrication, all baseline coupons were visually inspected at 20X. Cracks or machining marks perpendicular to the length of the coupon, visible at this magnification, were removed by polishing with 300- and 600-grit sandpaper. After polishing, coupons were re-inspected at 20X and repolished as required until the defects were removed. One machine was used to evaluate the fatigue behavior of all material at 100,000 cycles. No crossover testing was allowed.

c. For each substrate material, the maximum stress required to produce failure at 100,000 cycles, ± 20,000 cycles, using a stress ratio of 0.1 and a cycling frequency of 10 hertz was determined. This maximum stress for each material was used for all subsequent tests of high-pressure waterjet processed coupons per ASTM E466. All data were collected using the automated data acquisition system. Averages, standard deviations, and confidence intervals were calculated. Statistical analyses determined if significant differences between the baseline and high-pressure-waterjet-processed coupons existed.

4.3 FATIGUE CRACK GROWTH RATE EVALUATION

The objective of this test was to determine the effects of high-pressure water and chemical stripping on the FCGR of 2024-T3 bare, 2024-T3 clad, 7075-T6 bare, and 7075-T6 clad. The high-pressure waterjet post process data were compared to the test data from the chemically stripped coupons and the unpainted/as-received coupons to determine the effects of the high-pressure waterjet process. The following paragraphs discuss procedures for coupon preparation, processing, and testing for the fatigue evaluation.

4.3.1 Test Coupon Preparation.

4.3.1.1 To maintain trace-ability, a test identification number was scribed along the 3.5-inch (0.089-m) side of the coupon and below the locating hole on the unprocessed and unpainted side of the coupon. The numbering system follows.

FCGR-2024C-A

FCGR = fatigue notch back
2024C = metal designation = 2024-T3 clad
A = process description

4.3.1.2 A common coupon was used for all processing. FCGR coupons were machined from this common configuration for baseline and post-process testing. Following are the coupon preparation procedures for the baseline, chemically stripped, and high-pressure waterjet coupons.

a. The baseline coupons were cut directly from the sheet of material and tested per paragraph 4.3.3. For each substrate material, the maximum stress required to produce failure at 100,000 cycles, ± 20,000 cycles, using a stress ratio of 0.1 and a cycling frequency of 10 hertz was determined. This maximum stress for each material was used for all subsequent tests of high-pressure-waterjet-processed coupons per ASTM E466. All data were collected using the automated data acquisition system. Averages, standard deviations, and confidence intervals were calculated. Statistical analyses determined if significant differences between the baseline and high-pressure-waterjet-processed coupons existed.

b. Coupons for both chemical and high-pressure waterjet stripping were prepared for processing as follows.

Step	Description
1	**Coupons were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.**
2	**The coupon surfaces were coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, coupons were primed with Koroflex primer (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils. All coupons were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Coupons were air dried for at least 7 days, then aged at 210° F for 96 hours.**

4.3.2 Coupon Processing.

4.3.2.1 Baseline coupons for FCGR testing would be the as-received material. Coupons were cut from each substrate material and required no further processing. The following procedures were used to process chemically stripped and high-pressure waterjet blasted coupons:

a. After artificial aging, coupons for the chemically stripped FCGR tests were processed as follows.

Step	Description
1	Coupons were chemically stripped using TURCO 5351 to remove the paint.
2	A light to medium coat of the chemical stripper was applied uniformly using a non-metallic brush and allowed to dwell for 45-60 minutes without drying on the surface.
3	After the coating had loosened, five passes were made on the coupon's surface using MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type H, Class I, Form A aluminum wool.
4	The surface was rinsed with warm water at 100 - 120° F to remove the residue.
5	This procedure was repeated for three additional cycles using unpainted, chemically stripped coupons to simulate three additional stripping cycles before testing.

b. Coupons for the high-pressure-waterjet-blasted FCGR tests were processed from each substrate material. The coupons were waterjet blasted for four cycles. The first cycle removed all paint, and successive cycles simulated further paint stripping. An index of 0.1 inch between cycles was used to simulate robotic inconsistencies. The Koroflex and the polyurethane FCGR coupons were each blasted using 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate.

4.3.3 FCGR Test Procedures

4.3.3.1 The common set of coupons processed in the previous paragraph was fabricated into FCGR test coupons. Fabrication procedures followed coupon preparation procedures described in ASTM E647.

4.3.3.2 FCGR coupons were fabricated for the test baseline using as-received material. Sets of identically processed coupons were used for fabricating chemically stripping and high-pressure waterjet stripping test coupons. Each type of coupon was pre-cracked before testing to provide a sharpened and straightened crack of adequate size. The length of each crack was 0.04 inch and the maximum DK during pre-cracking did not exceed the stress intensity factor of 6 ksi-inch$^{1/2}$. The half-crack length after pre-cracking did not exceed 0.353 inches.

4.3.3.3 The FCGR test was performed on each coupon to establish a baseline FCGR for the DK range of 6 ksi-in$^{1/2}$ - 16 ksi-in$^{1/2}$ per ASTM E647. All crack lengths were optically measured using a 30 X magnification, traveling microscope. The maximum stress was 6,250 psi, and a test frequency of 10 hertz was used. Ten coupons, minimum, of each type were used to establish the baseline.

4.3.3.4 FCGR was calculated using the incremental polynomial method. Baseline and processed specimens were compared statistically at ΔK values of 7, 8, 11, and 15 ksi-in$^{1/2}$. Since crack readings probably were not made at precisely the desired ΔK value, da/dn values were obtained by curve fitting using the 7-point ASTM method in ASTM E647. This involves selecting the nearest point to the desired ΔK values as the central point and calculating a representative da/dn at the desired ΔK for the specimen.

4.4 CORROSION EVALUATION - SALT FOG EXPOSURE

The objective of this test was to determine the effects of the high-pressure water and chemical stripping processes on the salt fog corrosion behavior of 2024-T3 clad, 2024-T3 bare, 7075-T6 clad, and 7075-T6 bare. The procedures for preparing, processing, and testing the coupons follow.

4.4.1 Test Coupon Preparation.

4.4.1.1 To maintain traceability, a test coupon identification number was scribed along the 3.5-inch (0.089-m) side of the coupon and below the locating hole on the unprocessed and unpainted side of the coupon. The numbering system follows.

COR-2024C-A (PT, Chem, WTR, SCR)

COR	=	corrosion
2024C	=	metal designation = 2024-T3 clad
A	=	process description
PT	=	designated if painted
Chem	=	designated if chemically processed
WTR	=	designated if water processed
PT	=	designated if repainted
SCR	=	designated if scribed

4.4.1.2 A common coupon was used for all corrosion tests. Corrosion coupons were fabricated for the following exposures:

- unpainted/salt fog
- painted/HPW processed/salt fog
- painted/chemical processed/salt fog
- painted/unprocessed/salt fog
- painted/chemical processed/painted/salt fog
- painted/HPW processed/painted/salt fog
- painted/HPW processed/painted/diagonal scribe/salt fog
- painted/chemical processed/painted/diagonal scribe/salt fog

4.4.1.3 The following procedures were used to prepare the corrosion coupons for processing and/or salt fog exposure:

Step	**Description**
1	**Coupons were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.**
2	**Coupon surfaces were coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, coupons were primed with Koroflex primer (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils. All coupons were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Coupons were air dried for at least 7 days, then aged at 210° F for 96 hours.**
5	**An X was hand scribed into the surfaces of a set of scribed coupons with a razor blade from corner to corner, using enough pressure to penetrate the painted layer.**

4.4.2 Coupon Processing.

4.4.2.1 Two sets of coupons were used for the baseline evaluation. These included:

Set 1: unpainted, unprocessed as-received, and tested.

Set 2: painted, unprocessed, and tested.

4.4.2.2 Coupons processed for high-pressure waterjet evaluation were blasted for four cycles. The first cycle removed all paint and successive cycles simulated further paint stripping. An index of 0.1 inch between cycles was used to simulate robotic inconsistencies. The coupons were blasted at 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate. Three sets of coupons were painted, then processed using the high-pressure waterjet. These sets included:

Set 1: painted, waterjet processed, and tested.

Set 2: painted, waterjet processed, repainted, and tested.

Set 3: painted, waterjet processed, repainted, scribed, and tested.

4.4.2.3 After artificial aging, coupons processed for chemical stripping evaluation were chemically stripped using TURCO 5351. A light to medium coat of the chemical stripper was applied uniformly using a non-metallic brush and allowed to dwell for 45-60 minutes without drying on the surface. After the coating had loosened, five passes were made on the coupon's surface using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool. The surface was rinsed with warm water at 100-120° F to remove the residue. This procedure was repeated for three additional cycles using unpainted, chemically stripped coupons to simulate three additional stripping cycles before testing. Three sets of coupons were painted and then chemically stripped. These sets included:

Set 1: painted, chemically stripped, and tested.

Set 2: painted, chemically stripped, repainted, and tested.

Set 3: painted, chemically stripped, repainted, scribed, and tested.

4.4.3 Test Procedures.

All salt fog exposure tests were performed per ASTM B117, Standard Test Method of Salt Spray (Fog) Testing, for 30 days. Coupons were inspected every 10 days, and any initiation or progression of corrosion was reported. Weight loss after exposure was determined. All corrosion results were compared with the baseline coupons (i.e., unpainted, salt fog and painted, salt fog) to determine if the high-pressure waterjet process adversely effected the corrosion resistance.

4.5 SEALANT INTEGRITY EVALUATION

The objective of the test was to evaluate the effects of the high-pressure water and chemical stripping processes on the sealant integrity of butt joints and lap joints. The following paragraphs discuss the preparation, processing, and test procedures for the sealant integrity of butt joints.

4.5.1 Butt Joint Panels.

4.5.1.1 Butt joint panels were fabricated using 2024-T3 clad, conforming to Federal Specification QQ-A-250/5. Five panels each, of three configurations, were fabricated.

Configuration 1: **3/32-inch-diameter countersink rivets (MS 20426AD3-4) installed dry.**

Configuration 2: **3/32-inch-diameter countersink rivets (MS 20426AD3-4) dipped in MIL-C-23377 and installed wet.**

Configuration 3: **3/32-inch-diameter countersink rivets (MS 20426AD3-4) dipped in Military Sealant Specification (MIL-S) 8802 and installed wet, cherry locks (NAS 1399-6-2) dipped in MIL-S-8802 and installed wet, and jo-bolts (NAS-1769-6-2) dipped in MIL-S-8802 and installed wet.**

a. Configuration 1 panels were fabricated per Figure 35. All bonding surfaces were cleaned using an organic solvent such as methyl ethyl ketone (MEK) and a lint-free cloth before applying a MIL-S-8802 primer and sealant. After sealant application, butt joint panels were mated, and the gap was filled with sealant. The panels were then riveted using 3/32-inch diameter countersink rivets (MS 20426AD3-4). After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the underside of the butt joints. Then the panels were painted as follows:

Step	**Description**
1	**Panels were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.**
2	**Panels' surfaces were coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, panels were primed with Koroflex primer (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils. All panels were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Panels were not artificially aged to prevent thermal warping, which may have resulted in sealant delamination along the butt joint.**

b. Configuration 2 panels were fabricated per Figure 36. All bonding surfaces were cleaned using an organic solvent such as MEK and a lint-free cloth before applying a MIL-S-8802 epoxy primer and sealant. After sealant application, butt joint panels were mated, and the gap was filled with sealant. The panels were then riveted as shown, using 3/32-inch-diameter countersink rivets (MS 20426AD3-4). The rivets were dipped in MIL-C-23377 epoxy paint primer and installed. After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the underside of the butt joints. Then the panels were painted the same as configuration 1.

c. Configuration 3 panels were fabricated per Figure 37. All bonding surfaces were cleaned using an organic solvent such as MEK and a lint-free cloth before applying a MIL-S-8802 epoxy primer and sealant. After sealant application, butt joint panels were mated, and the gap filled with sealant. The panels were then riveted as shown, using 3/32-inch-diameter countersink rivets (MS 20426AD3-4), cherry locks (NAS 1399-6-2), and jo-bolts (NAS-1769-6-2). The rivets were dipped in MIL-C-23377 epoxy paint primer; the cherry locks and jo-bolts were dipped in MIL-S-8802 primer and sealant. After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the underside of the butt joints. Then the panels were painted the same as configurations 1 and 2.

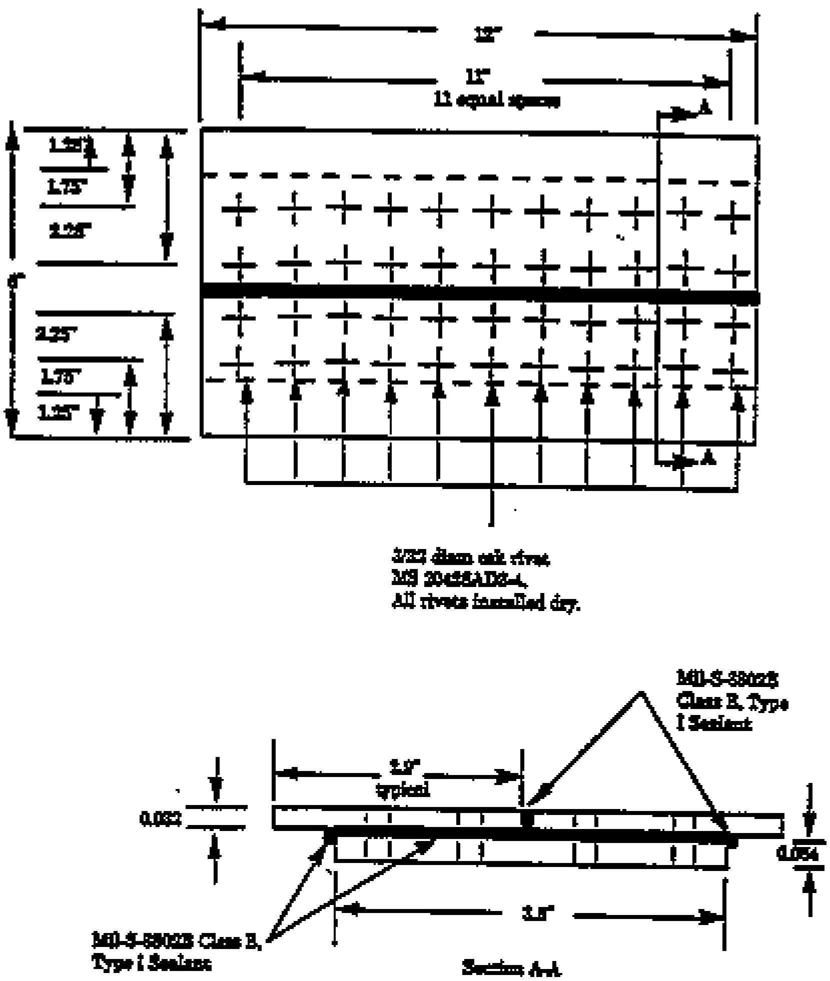


Figure 35. Butt joint panel, configuration 1.

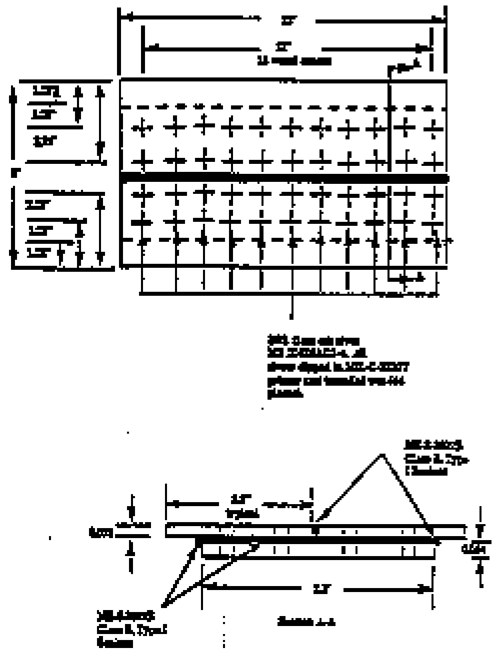


Figure 36. Butt joint panel, configuration 2.

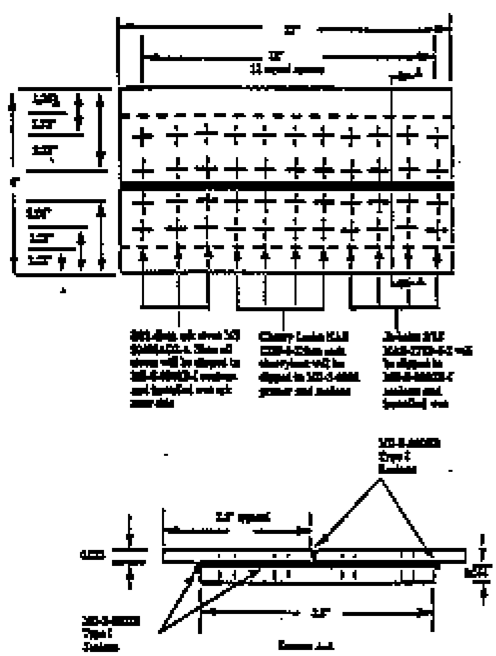


Figure 37. Butt joint panel, configuration 3.

4.5.1.2 Panel Processing.

a. Panels were high-pressure waterjet blasted, using three different pass scenarios. One pass per panel was used. The first scenario was to remove the paint next to the butt joint without blasting the sealant. The second scenario was to remove the paint next to the butt joint and did blast the sealant in the butt joint. The third scenario was to remove the paint next to the butt joint, blast the sealant in the butt joint, and remove the paint next to the butt joint on the opposite side. The panels were blasted at 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate.

b. Butt joints of each configuration were chemically stripped with TURCO 5351. A light to medium coat of the chemical stripper was applied uniformly with a non-metallic brush and allowed to dwell for 45-60 minutes drying on the surface. After the coating had loosened, five passes were made on the panel's surface using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool. The surface was rinsed with warm water at 100-120° F to remove the residue.

4.5.1.3 Test Procedures.

Each butt joint, both high-pressure waterjet and chemically stripped, was cut perpendicular to the butt joint and inspected for sealant removal and water intrusion. The amount of sealant removed and the presence of any residual water were documented.

4.5.2 Lap Joint Panels.

4.5.2.1 The lap joint panels were fabricated using 2024-T3 clad, conforming to Federal Specification QQ-A-250/5. Five panels each, of three configurations, were fabricated.

Configuration 1: **3/32-inch-diameter countersink rivets (MS 20426AD3-4) installed dry.**

Configuration 2: **3/32-inch-diameter countersink rivets (MS 20426AD3-4) dipped in MIL-C-23377 and installed wet.**

Configuration 3: **3/32-inch-diameter countersink rivets (MS 20426AD3-4) dipped in MIL-S-8802 and installed wet, cherry locks (NAS 1399-6-2) dipped in MIL-S-8802 and installed wet, and jo-bolts (NAS-1769-6-2) dipped in MIL-S-8802 and installed wet.**

a. Configuration 1 panels were fabricated per Figure 38. All bonding surfaces were cleaned using an organic solvent such as MEK and a lint-free cloth before applying a MIL-S-8802 primer and sealant. After sealant application, lap joint panels were mated, and the gap was filled with sealant. The panels were then riveted using 3/32-inch-diameter countersink rivets (MS 20426AD3-4). After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the underside of the lap joints. Then the panels were painted as follows:

Step	**Description**
1	**Panels were cleaned using a detergent solution conforming to MIL-C-87936 Type I, then acid etched using a solution conforming to MIL-C-38334.**
2	**Panels' surfaces were coated with a chromate conversion coating conforming to MIL-C-81706 according to MIL-C-5541E.**
3	**After drying, coupons were primed with Koroflex primer (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils. All coupons were then coated with MIL-C-83286 polyurethane to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Panels were not artificially aged to prevent thermal warping, which may result in sealant delamination along the lap joint.**

b. Configuration 2 panels were fabricated per Figure 39. All bonding surfaces were cleaned using an organic solvent such as MEK and a lint-free cloth before applying a MIL-S-8802 epoxy primer and sealant. After sealant application, lap joint panels were mated, and the gap was filled with sealant. The panels were then riveted as shown, using 3/32-inch-diameter countersink rivets (MS 20426AD3-4). The rivets were dipped in MIL-C-23377 epoxy paint primer and installed. After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the underside of the lap joints. Then the panels were painted the same as configuration 1.

c. Configuration 3 panels were fabricated per Figure 40. All bonding surfaces were cleaned using an organic solvent such as MEK and a lint-free cloth before applying a MIL-S-8802 epoxy primer and sealant. After sealant application, lap joint panels were mated, and the gap was filled with sealant. The panels were then riveted as shown, using 3/32-inch-diameter countersink rivets (MS 20426AD3-4), cherry locks (NAS 1399-6-2), and jo-bolts (NAS-1769-6-2). The rivets were dipped in MIL-C-23377 epoxy paint primer; the cherry locks and jo-bolts were dipped in MIL-S-8802 primer and sealant. After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the underside of the lap joints. Then the panels were painted the same as configurations 1 and 2.

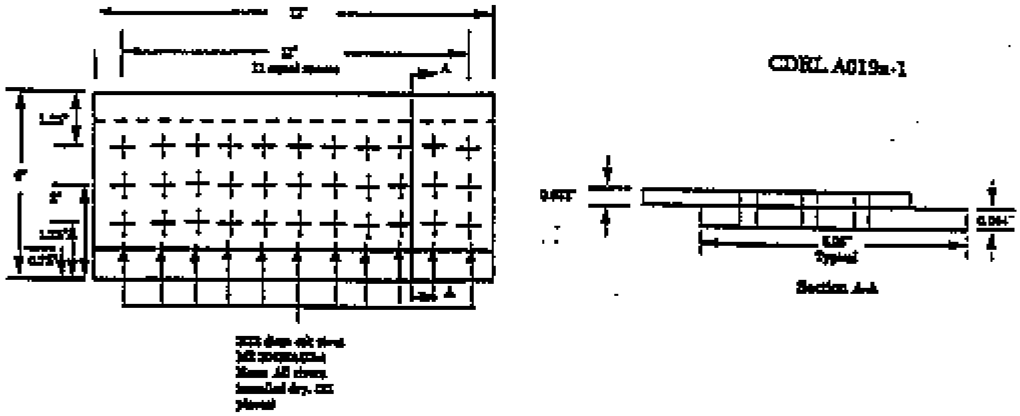


Figure 38. Lap joint panel, configuration 1.

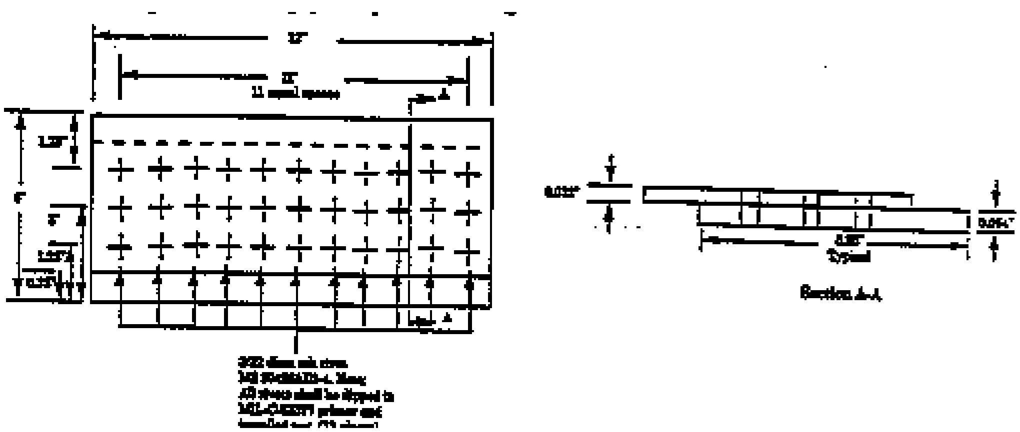


Figure 39. Lap joint panel, configuration 2.

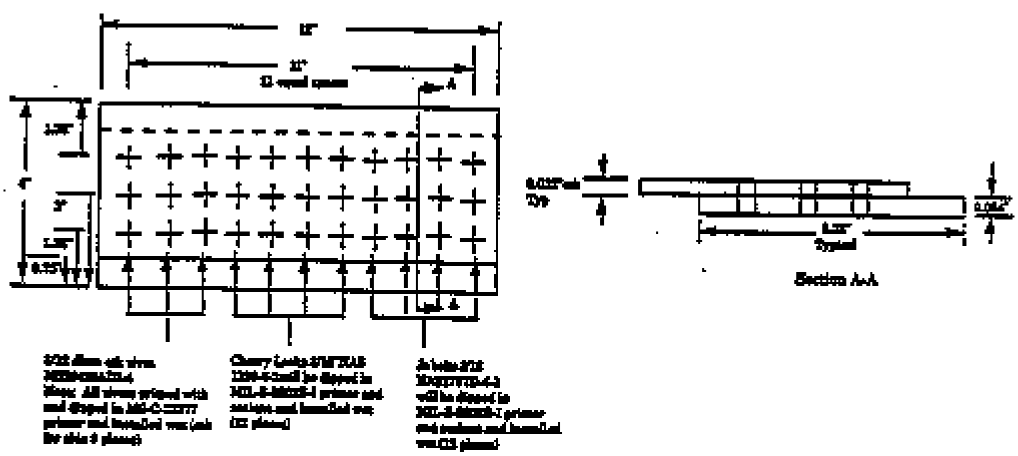


Figure 40. Lap joint panel, configuration 3.

4.5.2.2 Panel Processing.

a. Panels were high-pressure waterjet blasted, using three different scenarios. One pass per panel was used. The first scenario was to remove the paint next to the lap joint without blasting the sealant. The second scenario was to remove the paint next to the lap joint and blast the sealant in the lap joint. The third scenario was to remove the paint next to the lap joint, blast the sealant in the lap joint, and remove the paint next to the lap joint on the opposite side. The panels were blasted at 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate.

b. Lap joints of each configuration were chemically stripped using TURCO 5351. A light to medium coat of the chemical stripper was applied uniformly with a non-metallic brush and allowed to dwell for 45-60 minutes, drying on the surface. After the coating had loosened, five passes were made on the panel's surface using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool. The surface was rinsed with warm water at 100-120° F to remove the residue.

4.5.2.3 Test Procedures.

Each lap joint, both high-pressure waterjet and chemically stripped, was cut perpendicular to the lap joint and inspected for sealant removal and water intrusion. The amount of sealant removed and the presence of any residual water were documented.

4.6 WATER INTRUSION EVALUATION

4.6.1 Butt Joint.

4.6.1.1 The butt joint panels for the water intrusion evaluation were prepared and processed the same as for the sealant integrity evaluation described in paragraph 4.5.1. Also, the panels were prepared and processed in the same configurations and numbers.

4.6.1.2 All butt joint configurations processed using the high-pressure waterjet or chemical stripping were inspected using neutron radiography before and after processing. General procedures for neutron radiography followed Specification No. 1002, Revision C, Neutron Radiographic Inspection of Non-Ordinance Devices, developed by Aerotest Operations, Inc., of San Ramon, CA.

4.6.2 Lap Joint.

4.6.2.1 The lap joint panels for the water intrusion evaluation were prepared and processed the same as for the sealant integrity evaluation described in paragraph 4.5.2. Also, the panels were prepared and processed in the same configurations and numbers.

4.6.2.2 **All lap joint configurations processed using the high-pressure waterjet or chemical stripping were inspected using neutron radiography before and after processing. General procedures for neutron radiography followed Specification No. 1002, Revision C, Neutron Radiography Inspection of Non-Ordinance Devices, developed by Aerotest Operations, Inc.**

4.6.3 Fastener Panel.

The following paragraphs discuss the preparation, processing and test procedures for water intrusion testing of a fastener panel configuration defined by OC-ALC and typical of the fastener panels on aircraft refurbished at OC-ALC.

4.6.3.1 Test Panel Preparation.

Fastener panels were fabricated using 2024-T3 clad, conforming to Federal Specification QQ-A-250/5. All bonding surfaces were cleaned using an organic solvent such as MEK and a lint-free cloth before applying the sealant. Then a primer specified for MIL-S-8802 sealant by the sealant manufacturer was applied to one of the panels. The panels were riveted together as shown in Figure 41, using 3/32-inch-diameter countersink rivets (MS 20426AD3-4). After the fasteners were attached, a bead of MIL-S-8802 sealant was applied along the edge of the fastener panel.

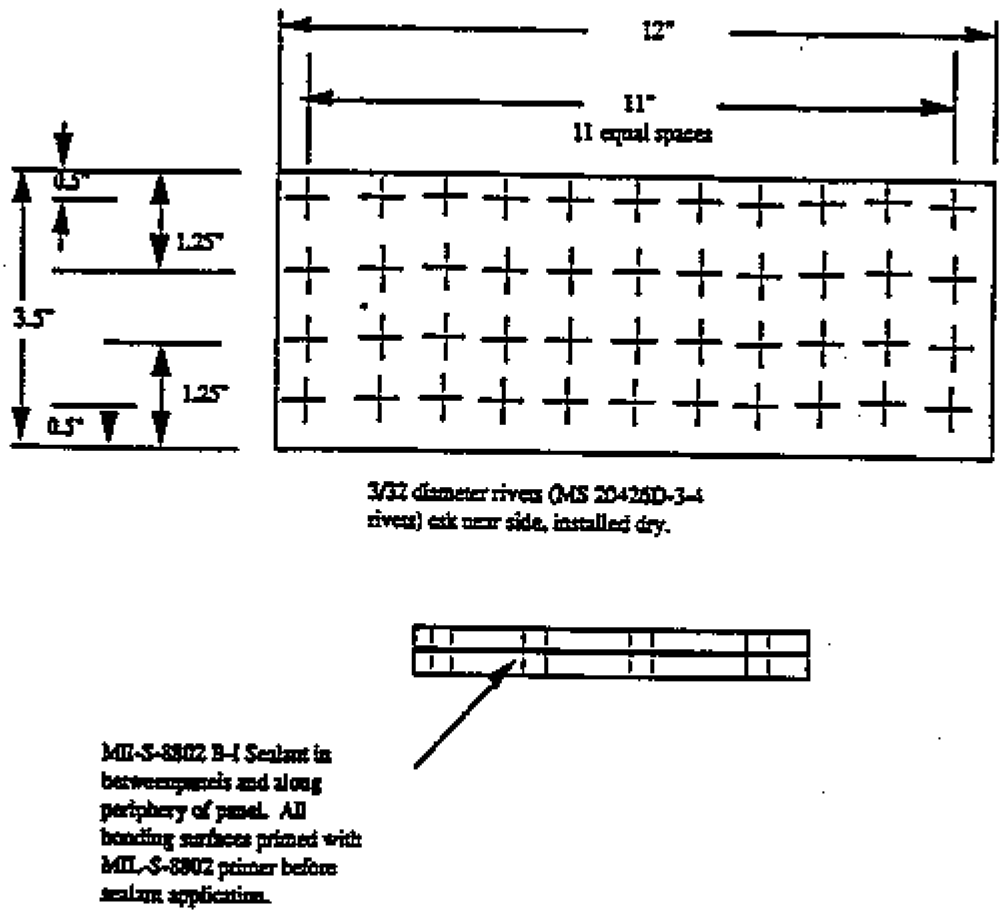


Figure 41. Fastener panel configuration.

4.6.3.2 Coupon Processing.

a. The panels for high-pressure waterjet blast tests were completely stripped using 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate.

b. The panels for the chemical strip tests were stripped using TURCO 5351. A light to medium coat of the chemical stripper was applied uniformly with a non-metallic brush and allowed to dwell for 45-60 minutes without drying on the surface. After the coating had loosened, five passes were made on the panel's surface using a MIL-A-9962 Type I nylon abrasive, followed by five passes using an A-A-1044 Type II, Class I, Form A aluminum wool. The surface was rinsed with warm water at 100-120° F to remove the residue.

4.6.3.3 Test Procedures.

All fastener panels processed using the high-pressure waterjet or chemical stripping were inspected using neutron radiography before and after processing. General procedures for neutron radiography were followed.

4.7 REPAINTABILITY EVALUATION

The objective of this test was to evaluate the effects of the high-pressure waterjet on the repaintability of 2024-T3 clad, 2024-T3 bare, 7075-T6 clad, and 7075-T6 bare. Common coupons were painted, processed, repainted, and tested to determine paint adhesion.

4.7.1 Test Coupon Preparation and Processing.

4.7.1.1 To maintain trace-ability, a test coupon identification number was scribed along the 3.5-inch (0.089-m) side of the coupon and below the locating hole on the unprocessed and unpainted side of the coupon. The numbering system follows.

RP = repaintability coupon

2024C = alloy designation

A = WTR: water processed

CH = Chemically Processed

4.7.1.2 Repaintability coupons were prepared and processed from 2024-T3 clad, 2024-T3 bare, 7075-T6 clad, and 7075-T6 bare. The same procedures as were used to prepare and process the corrosion coupons for testing and/or salt fog exposure. The preparation and processing procedures are described in paragraph 4.5.

4.7.2 Test Procedures.

The effects of high-pressure waterjet and chemical stripping on repaintability were evaluated by comparing the post-process adhesion values to the adhesion values for unprocessed, painted coupons. The adhesion was evaluated per ASTM D3359, Standard Test Methods for Measuring Adhesion by Tape Test. Test method B was used.

4.8 SPOT WELD INTEGRITY

The objective of this test was to determine whether the high-pressure waterjet process would break spot welds on flat and bent panels. This test was performed at the direction of the KC-135 Program Office at OC-ALC to address process issues concerning integrity in spot welded skin areas of the aircraft.

4.8.1 Test Panel Preparation.

4.8.1.1 Test panels for the spot weld, eddy current inspection were prepared using two configurations: flat and 2-inch radius bend. Panels were constructed from the following materials:

- **2024-T3 clad, 0.032-inch**
- **7075-T6 clad, 0.032-inch**
- **2024-T3 clad, 0.080-inch**
- **7075-T6 clad, 0.080-inch**

4.8.1.2 For each material, an 8-inch x 8-inch x 0.032-inch or 0.080-inch panel of the selected material was spot welded to a 12-inch x 12-inch x 0.032-inch or 0.080-inch panel of the same material. The panels were prepared per Military Welding Standard (MIL-W) 6858 Gr 1, Class B. Three pitch sizes were used: 0.25-inch, 0.50-inch, 1.0-inch. Figure 42 shows the pitch size layout. The distance between each spot was measured from center to center. Two panels were constructed. One panel was bent over a 2-inch radius mandrel to 90 degrees along the line of symmetry after spot welding.

4.8.1.3 The same procedures used for painting panels for the sealant integrity evaluation, paragraph 4.5.1, were used to paint the panels before performing the pre-process inspection.

4.8.2 Panel Processing.

The painted surface of all panels was initially stripped for two stripping cycles at 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate. The first cycle removed all the paint, and the second cycle simulated a stripping cycle. The nozzle was oriented 90 degrees to the panel during stripping. The panels were clamped along the edges. After the first two stripping cycles, the panels were repainted then stripped for two additional cycles. The first cycle removed all the paint, and the second cycle simulated stripping.

4.8.3 Test Procedures.

4.8.3.1 Each spot-welded panel was non-destructively inspected per T.O. 1C-135-36, with a ZETEC MIZ-10A a portable variable frequency impedance plane analysis eddy current instrument. The probe was a Nortec SP 10A or equivalent. OC-ALC furnished an inspection standard as outlined in Figure 8-4-3, Detail 1 of T.O. 1C-135-36, to calibrate the eddy current equipment.

4.8.3.2 All panels underwent eddy current inspection per T.O. 1C-135-36. A frequency of 10 kilohertz was used for inspection with an initial gain of 500. All spot welds of all panels were inspected using a cross pattern. Cracked or broken spot welds were identified and recorded but not repaired.

4.8.3.3 After four stripping cycles, a post-process inspection was performed. All panels were eddy current inspected per T.O. 1C-135-36. A frequency of 10 kilohertz was used for inspection with an initial gain of 500. All spot welds of all panels were inspected in a cross pattern. Cracked or broken spot welds were identified and recorded. Any differences in spot weld integrity between the baseline panels and processed panels were recorded.

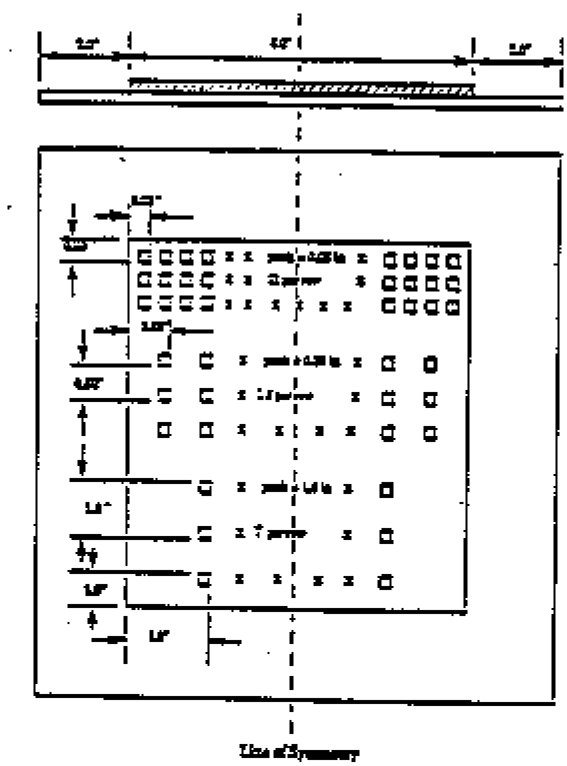


Figure 42. Flat panel configuration for spot weld testing.

4.9 ADDITIONAL MATERIALS EVALUATION

4.9.1 Materials.

The following additional metals and coatings were identified to validate the stripping efficiency of the high-pressure waterjet process.

4.9.1.1 Metals.

Listed below are the metals used during additional materials testing:

- **2424-T81 Clad**
- **6061-T6 Bare**
- **17-4 Stainless Steel**
- **Ti-6AI-4V**
- **7178-T6 Bare**
- **4340 Steel**
- **AZ91C - Magnesium**

4.9.1.2 Coating System.

Listed below are the coatings used during the additional materials testing. The stripping efficiency of the high-pressure waterjet process for these coatings was investigated using 2024-T3 clad panels only.

- · **Water Borne Epoxy**
- **Self Priming Topcoat**
- **Polysulfide**

4.9.2 Test Panel Preparation.

4.9.2.1 Aluminum and titanium panels were prepared as follows:

Step	Description
1	All aluminum and titanium panels were cleaned, acid etched, chromate conversion coated, and painted.
2	Panels were cleaned using a detergent solution conforming to MIL-C-87936, then acid etched using a solution conforming to MIL-C-38334.
3	Then panel surfaces were chromate conversion coated using a solution conforming to MIL-C-81706.
4	After drying, panels were primed with Koroflex (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils.

5 Then a MIL-C-83286 polyurethane topcoat was applied to all panels to a total dry film thickness of 2.2 - 3.2 mils.

6 Panels were air dried for at least 7 days, then aged at 210° F for 96 hours.

4.9.2.2 Steel panels were prepared as follows:

Step	**Description**
1	**All steel panels were cleaned per MIL-C-10578D using a solution of phosphoric acid to clean and prepare the surface.**
2	**After drying, panels were primed with Koroflex (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils.**
3	**Then a MIL-C-83286 polyurethane topcoat was applied to all panels to a total dry film thickness of 2.2 - 3.2 mils.**
4	**Panels were air dried for at least 7 days, then aged at 210° F for 96 hours.**

4.9.2.3 Magnesium parts were prepared as follows:

Step	**Description**
1	**All magnesium parts were cleaned using a chromic acid solution applied with an acid resistant brush and allowed to dwell for 15 minutes.**
2	**The solution was flushed with room temperature water as often as necessary to remove all corrosion products until the surface was bright metallic in appearance.**
3	**After cleaning, and before painting, the surface was pre-treated per MIL-M-3171C. The panels were primed with Koroflex (DeSoto 823x439) to a dry film thickness of 0.6 - 0.8 mils.**
4	**Then a MIL-C-83286 polyurethane topcoat was applied to all coupons to a total dry film thickness of 2.2 - 3.2 mils.**
5	**Panels were air dried for at least 7 days, then aged at 210° F for 96 hours.**

4.9.3 Panel Processing.

Two panels of each material were blasted with the high-pressure waterjet at 24,000 psi, 1.3-inch standoff, and a 1.25-inch/second travel rate. Only one 3.5-inch-wide pass was made on the first panel. Three passes were made on the second panel, stripping approximately 9 inches.

4.9.4 Once the panels were processed, the amount of paint removed from each sub-strate was evaluated. Any differences between stripping rates for additional materials and standard 2024-T3 clad and bare, and 0.032-inch-thick 7075-T6 clad and bare, were identified and recorded.

4.10 TEST RESULTS

4.10.1 Unnotched Fatigue Test Results - 100,000 cycles.

4.10.1.1 Al 2024-T3 Clad.

a. High-pressure waterjet and chemically stripped coupons were tested for the maximum stress required to produce failure in 100,000 cycles for the unpainted/as-received 2024-T3 clad coupons. The cycles to failure for each test condition, at a 90-percent confidence level, were calculated and a statistical comparison was made between the chemically stripped, high-pressure-waterjet-blasted, and the unpainted/as-received coupons to determine if there were differences in the data. The cycles to failure for each coupon for the process conditions were recorded and a statistical analysis performed. The cycles to failure for each test condition, at a 90-percent confidence level, were as follow.

Unpainted/As-received	**112,854 - 121,860 cycles**
Chemically Stripped	**82,601 - 104,007 cycles**
High-pressure Water	**94,005 - 105,031 cycles**

b. The chemically and the high-pressure-waterjet-stripped coupons had lower fatigue lives than the unpainted/as-received coupons. However, there is no statistical difference between the fatigue life data for the high-pressure-waterjet and chemically stripped coupons.

c. From the statistical data distribution shown in Figure 43 observing two sample populations, differences indicated that coupon preparation methods and/or the stripping processes may be affecting fatigue life. Since the data from the high-pressure waterjet process is not statistically different from the chemical process, the reduction may not be related to the stripping process, but to the coupon preparation method.

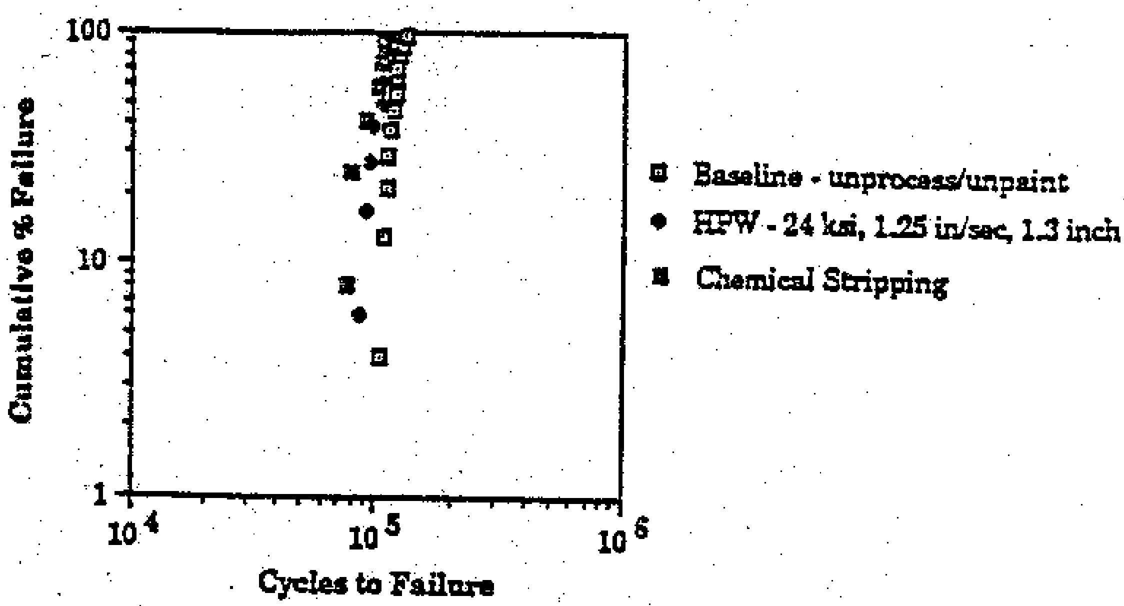


Figure 43. Statistical logarithmic data distribution for 2024-T3 alclad.

d. The reduced fatigue life for 2024-T3 clad coupons may be caused by the artificial aging process in which the coupons are post cured at 210° F (99° C) for 96 hours before processing. Mil-Handbook 5 indicates that the 2024-T3 coupons should not be exposed to temperatures in the range of 150-500° F, since the precipitation characteristic of this naturally aged alloy can be affected by prolonged exposure, resulting in changes to the mechanical properties. No work is planned within the scope of this study to validate the mechanism responsible for the fatigue loss.

e. Because the high-pressure waterjet process is an impingement process that may induce compressive residual stresses on the impinging surface and, since residual stresses can increase fatigue life, increased fatigue life might be expected to occur after high-pressure waterjet processing. However, as shown by the cycles to failure data shown in paragraph 4.10.1.1.a and the statistical data distribution in Figure 43, the coupons processed by high-pressure waterjet had lower fatigue lives than unpainted/as-received coupons and the same fatigue lives of chemically processed coupons. The lack of effect caused by chemical stripping can be better understood by considering the waterjet energy dissipation mechanism for 2024-T3 clad. Because the clad layer is made of a soft, malleable aluminum, which is easily deformed, it can dissipate the waterjet's impact. As a result, no energy from the waterjet's impact is available to create residual stresses in the substrate. Consequently, the fatigue life of coupons processed using the high-pressure waterjet did not show any more fatigue life than chemically processed coupons.

4.10.1.2 Al 2024-T3 Bare.

a. High-pressure waterjet and chemically stripped coupons were tested for the maximum stress required to produce failure in 100,000 cycles for the unpainted/as-received

2024-T3 bare coupons. The cycles to failure for each test condition, at a 90 percent confidence level, were calculated and statistical comparisons made between the chemically stripped, high-pressure waterjet blasted, and the unpainted/as-received coupons to determine if there were differences in the data. The cycles to failure for each test condition, at a 90-percent confidence level, were as follow.

Unpainted/As-received	**102,858 - 125,678 cycles**
Chemically Stripped	**76,328 - 101,133 cycles**
High-pressure Water	**94,391 - 115,094 cycles**

b. The fatigue lives of chemically stripped 2024-T3 bare coupons were lower than those of the unpainted/as-received and the high-pressure waterjet processed coupons. However, there is no statistical difference between the fatigue data for high-pressure waterjet blasted and unpainted/as-received coupons.

c. The statistical data distribution in Figure 44 shows two sample populations. One population includes unpainted/as-received and high-pressure waterjet samples. The second population includes the chemically stripped samples. Since 2024-T3 is a naturally aged alloy, the chemically stripped coupons reflect the effects of artificial aging during the sample preparation. Although a similar artificial aging effect might be expected in coupons processed with the high-pressure waterjet, this effect was not observed for 2024-T3 bare. The apparent difference in behavior of 2024-T3 bare and 2024-T3 clad after chemical and high-pressure waterjet processing may be related to the energy dissipation mechanism of the high-pressure waterjet process. During this process, water impinges the surface of the 2024-T3 bare, creating compressive stresses as shown by the Almen arc height data generated during process optimization. Since there is no extremely soft, malleable layer to absorb the water's impact as in the 2024-T3 clad, the energy is absorbed by the substrate and dissipated by compressive stresses. The fatigue life of high-pressure waterjet coupons before processing probably was similar to that of a chemically stripped coupon due to the artificial aging procedure. However, the compressive stresses created in the 2024-T3 bare during high-pressure waterjet processing increased the coupon's fatigue life, making it similar to the unpainted/as-received coupons. The chemically stripped cycles had lower fatigue lives than the ones processed by high-pressure waterjet.

4.10.1.3 Al 7075-T6 Clad.

a. High-pressure waterjet and chemically stripped coupons were tested for the maximum stress required to produce failure in 100,000 cycles for the unpainted/as-received 7075-T6 clad coupons. The cycles to failure for each test condition, at a 90-percent confidence level, were calculated and a statistical comparisons were made between the chemically stripped, high-pressure waterjet blasted, and the unpainted/as-received coupons to determine if there were differences in the data.

b. The fatigue lives of unpainted/as-received, high-pressure waterjet, and chemically stripped coupons were not statistically different from one another. The cycles to failure for each test condition, at a 90 percent confidence level, were as follow.

Unpainted/As-received	**109,903 - 133,147 cycles**
Chemically Stripped	**103,928 - 124,872 cycles**
High-pressure Water	**103,983 - 120,854 cycles**

c. Figure 45 shows the statistical data distribution. The sample populations appears to be similar, but the effects of the artificial aging process on the 7075-T6 coupons are not observed. The absence of this effect may be related to the artificial aging temperature being less than the precipitation heat treatment temperature. Typically, 7075-T6 coupons are solution heat treated at 900° F, followed by a precipitation-heat-treatment at 250° F for 24 hours. Because the artificial aging temperature is less than the precipitation-heat-treatment temperature, the alloy's microstructure is stable and unchanged by the artificial aging temperature. Consequently, chemically and high-pressure-waterjet-processed fatigue data were not significantly different than the unpainted/as-received data.

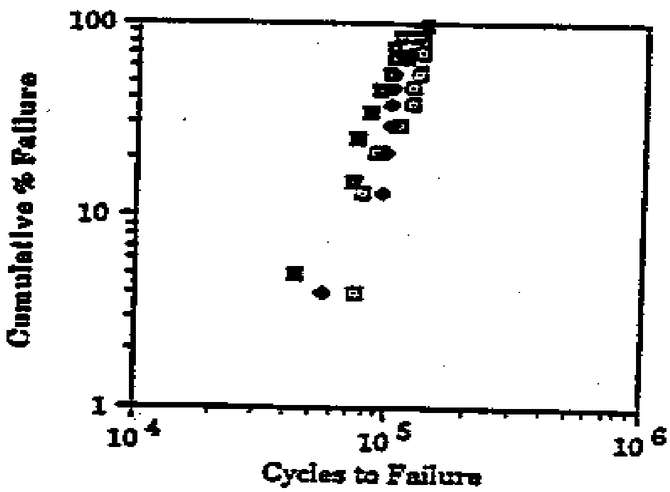


Figure 44. Statistical logarithmic data distribution for 2024-T3 bare.

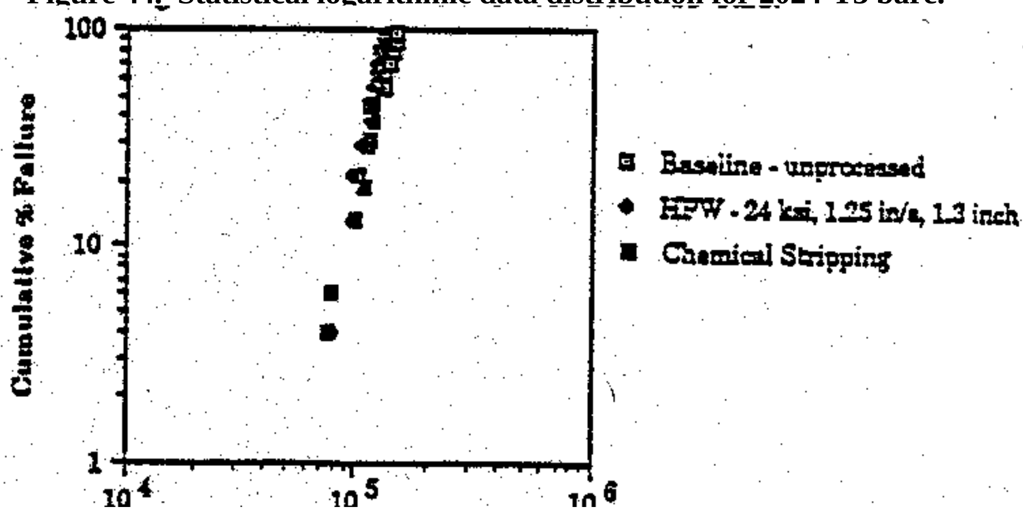


Figure 45. Statistical logarithmic data distribution for 7075-T6 Alclad.

4.10.1.4 Al 7075-T6 Bare.

a. High-pressure waterjet and chemically stripped coupons were tested for the maximum stress required to produce failure in 100,000 cycles for the unpainted/as-received 7075-T6 bare coupons. The cycles to failure for each test condition, at a 90 percent confidence level, were calculated. Then coupons stripped by the two methods were compared to unpainted/as-received coupons to determine if there were statistical differences in the data. The cycles to failure for each test condition, at a 90-percent confidence level, were as follow.

Unpainted/As-Received	**83,588 - 97,772 cycles**
Chemically Stripped	**57,671 - 81,641 cycles**
High-Pressure Water	**69,075 - 94,053 cycles**

b. Chemical stripping lowered the fatigue lives of 7075-T6 bare coupons when compared to unpainted/as-received coupons, while the high-pressure waterjet had little effect. Figure 46 shows the statistical data distribution. At the higher levels of cumulative percent failures, the data distributions for high-pressure waterjet and unpainted/as-received coupons are similar. At the lower levels of the cumulative percent failures, the data distributions for the high-pressure waterjet process differ from the unpainted/as-received coupons but are similar to the chemically processed coupons. This similarity at the low cumulative percent failures results in no statistical differences. No work was planned within the scope of the study to investigate the mechanism responsible for shifting the fatigue life distribution.

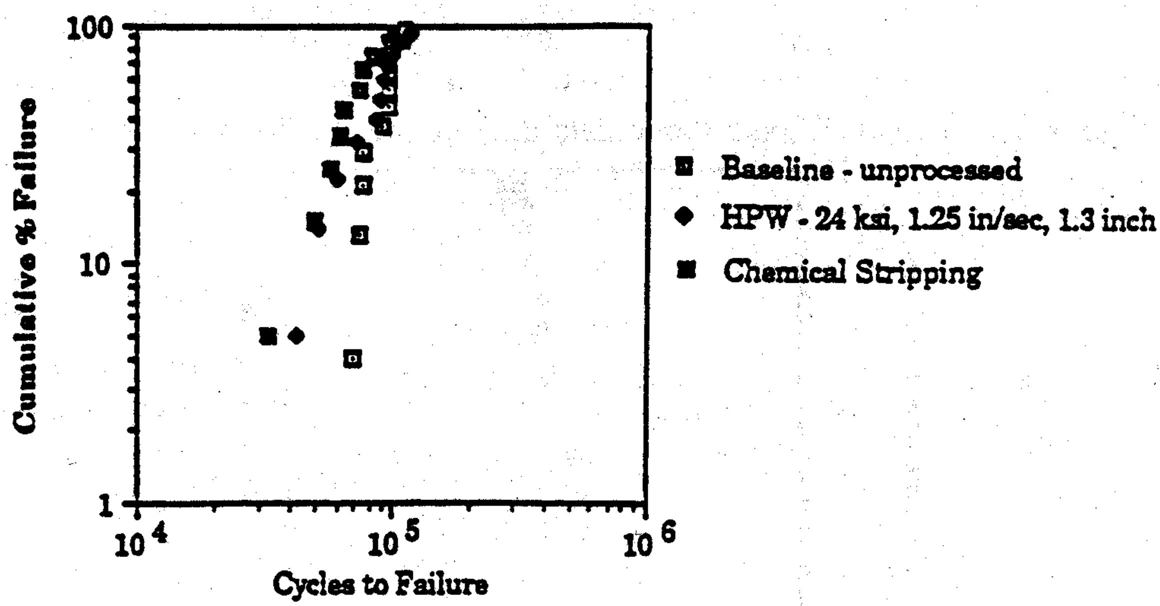


Figure 46. Statistical logarithmic data distribution for 7075-T6 bare.

4.10.2 Unnotched Fatigue Test Results - 500,000 cycles.

4.10.2.1 Al 2024-T3 Clad.

a. High-pressure waterjet and chemically stripped coupons were tested for the maximum stress required to produce failure in 500,000 cycles for the unpainted/as-received 2024-T3 clad coupons. The cycles to failure for each test condition, at a 90-percent confidence level, were calculated. Then coupons stripped by the two methods were compared to unpainted/as-received coupons to determine if there were statistical differences in the data. The cycles to failure for each test condition, at a 90-percent confidence level, were as follow.

Unpainted/As-received	**399,890 - 464,450 cycles**
Chemically Stripped	**251,157 - 310,560 cycles**
High-Pressure Water	**293,148 - 319,061 cycles**

b. Chemical and high-pressure waterjet stripping produced lower fatigue lives when compared to the unpainted/as-received 2024-T3 clad coupons. However, there is no significant difference between the fatigue data for high-pressure waterjet and chemically stripped coupons.

c. The statistical data distribution in Figure 47 shows behavior similar to that for the 100,000-cycle test. From the data distribution, two distinct sample populations are observed. As in the 100,000-cycle test, these two populations indicate that the coupon preparation method and/or the stripping processes may be affecting the fatigue life. Since the data from the high-pressure waterjet process is not statistically different from that of the chemical process, the reduction may not be related to the stripping process, but to the coupon preparation method.

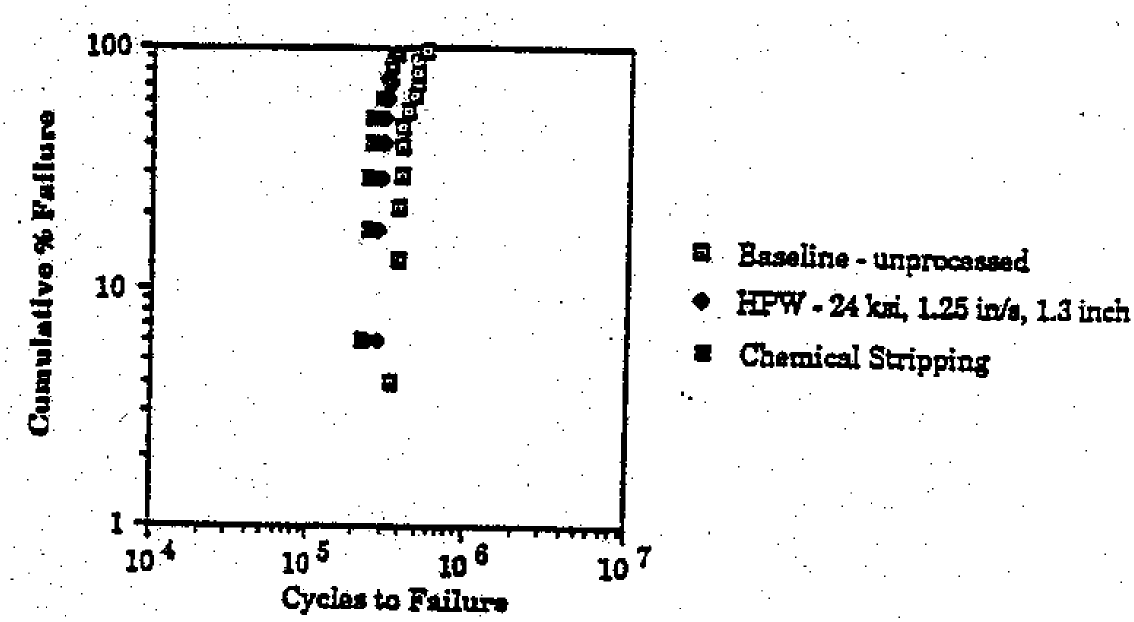


Figure 47. Statistical logarithmic data distribution for 2024-T3 alclad, 500,000 cycles.

d. The reduced fatigue life for 2024-T3 clad at 500,000 cycles, like 100,000 cycles, may be caused by the artificial aging process in which the coupons are post cured at 210° F (99° C) for 96 hours. Mil-Handbook 5 indicates that the 2024-T3 coupons should not be exposed to temperatures in the range of 150-500° F, since the precipitation characteristic of this naturally aged alloy can be affected by prolonged exposure. No work was planned within the scope of the study to validate the mechanism responsible for the fatigue loss.

e. No indications of changes due to residual stresses were found in the fatigue life after high-pressure waterjet processing. As discussed for 100,000 cycles, this lack of effect can be better understood by considering the waterjet energy dissipation mechanism for 2024-T3 clad.

4.10.2.2 Al 2024-T3 Bare.

a. High-pressure waterjet blasted and chemically stripped coupons were tested for the maximum stress required to produce failure in 500,000 cycles for the unpainted/as-received 2024-T3 bare coupons. The cycles to failure for each test condition, at a 90 percent confidence level, were calculated. Then coupons stripped by the two methods were compared to unpainted/as-received coupons to determine if there were statistical differences in the data. The cycles to failure for each test condition, at a 90-percent confidence level, were as follow.

Unpainted/As-received	**267,136 - 376,814 cycles**
Chemically Stripped	**166,520 - 476,734 cycles**
High-Pressure Water	**329,223 - 675,297 cycles**

b. A large data spread of 657,830 cycles occurred for the chemically stripped 2024-T3 bare coupons, whose minimum and maximum fatigue life values were 92,170 and 750,000 cycles, respectively. Neither the unpainted/as-received nor the high-pressure waterjet-processed coupons had such a large data spread. The minimum and maximum unpainted/as-received values were 201,240 and 454,730 cycles, respectively, giving a range of 253,490 cycles, while the high-pressure waterjet- processed coupons had minimum and maximum values of 173,420 and 654,180 cycles, respectively, for a range of 480,760 cycles. The wide data range had a significant impact on the statistical evaluation and there were no differences between any of the test conditions.

c. The statistical data distribution in Figure 48 shows two sample populations. One is made up of unpainted/as-received and the high-pressure waterjet-processed coupons. The second sample population includes the chemically stripped coupons. However, the chemically stripped coupons show two run-out data points at 750,000 cycles. These points cause the data distribution for the chemically stripped coupons to shift to the right, resulting in no statistical difference between the three sets of data when a statistical comparison is made.

d. If the two run-outs for the chemically stripped coupons are ignored the data turns out like that of the 100,000 cycle tests for 2024-T3 bare. When the run outs are not included, the cycles to failure for each test condition, at a 90-percent confidence level, were as follows.

Unpainted/As-received	**267,136 - 376,814 cycles**
Chemically Stripped	**132,883 - 265,586 cycles**
High-Pressure Water	**250,247 - 541,925 cycles**

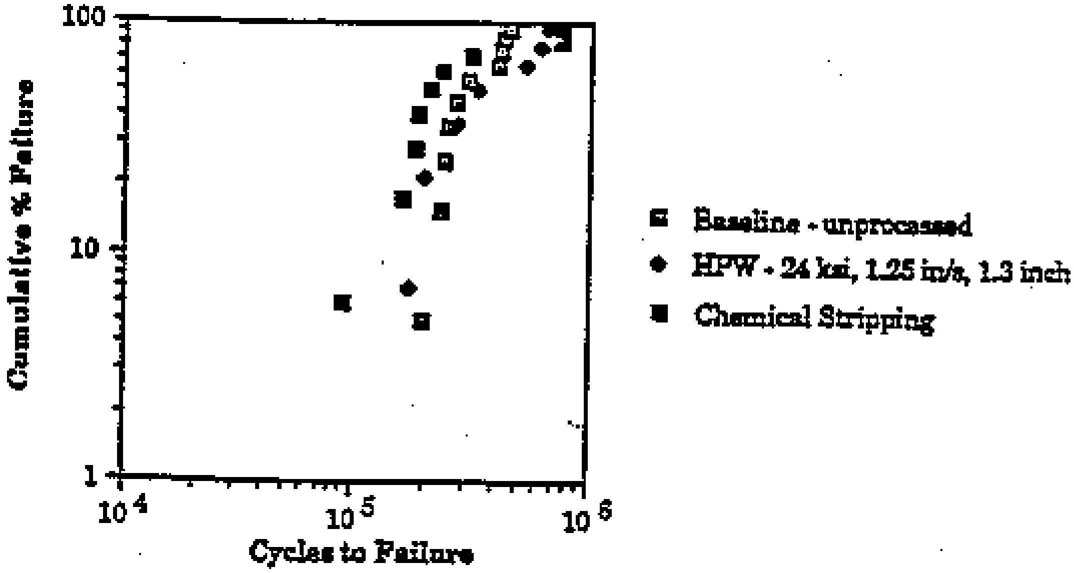


Figure 48. Statistical logarithmic data distribution for 2024-T3 bare, 500,000 cycles.

e. When the two run-out points for the fatigue data of chemically stripped 2024-T3 bare are not included in the data analysis, the fatigue life is lower after chemical stripping than for unpainted/as-received coupons.

f. The statistical data distribution in Figure 49 without the two run-out points is similar to that of 100,000-cycle unnotched fatigue. Two sample populations are apparent. One sample population includes the unpainted/as-received and the high-pressure waterjet process coupons, and the second, chemically stripped coupons.

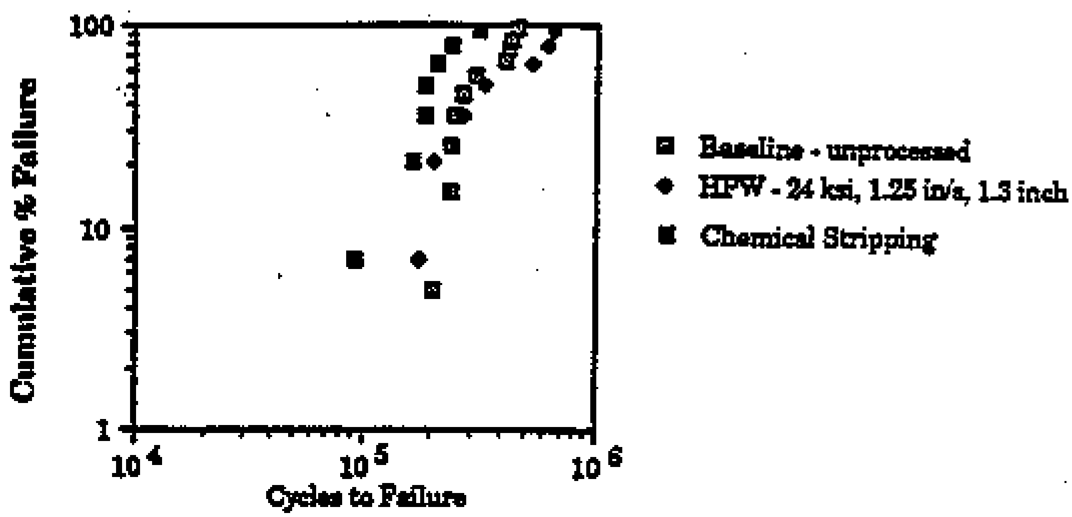


**Figure 49. Statistical logarithmic data distribution for 2024-T3 bare-
(no run-outs), 500,000 cycles.**

g. As with 100,000 cycles, the reduced fatigue life for 2024-T3 bare at 500,000 cycles may be caused by the artificial aging process in which the coupons are post cured at 210° F (99° C) for 96 hours. However, no work was planned within the scope of the study to validate the mechanism responsible for the fatigue loss.

h. During the high-pressure waterjet process, water impinges the surface of the 2024-T3 bare, creating compressive stresses as shown by the Almen arc height data generated during process optimization. Since there is no extremely soft, malleable layer to absorb the water's impact in the 2024-T3 clad, the energy is absorbed by the substrate and dissipated by the compressive stresses. The fatigue life of a high-pressure waterjet coupon before processing probably was similar to the chemically stripped coupon due to the artificial aging procedure. However, the compressive stresses created in the 2024-T3 bare during high-pressure waterjet processing increased the coupon's fatigue life making it similar to the unpainted/as-received coupons.

i. Based on the results of the testing for the fatigue life of 2024-T3 bare, the fatigue life evaluation used two cases. The first case included all data points for the chemically processed coupons. The second case excluded the two run-out conditions for the chemically stripped coupons. The basis for the second evaluation was that no run-out conditions were observed for the unpainted/as-received condition or the high-pressure waterjet-processed coupons. The two run-out data points were considered test artifacts. Therefore, the fatigue life of the high-pressure waterjet process was similar to the fatigue life of the chemical process. Test results of the second case showed that the fatigue life of the high-pressure waterjet process was greater than that of the chemical process.

4.10.2.3 Al 7075-T6 Alclad.

a. High-pressure-waterjet-processed and chemically stripped coupons were tested for the maximum stress required to produce failure in 500,000 cycles for the unpainted/as-received 7075-T6 alclad coupons. The cycles to failure for each test condition, at a 90-percent confidence level, were calculated. Then coupons stripped by the two methods were compared to unpainted/as-received coupons to determine if there were statistical differences in the data. The cycles to failure for each test condition, at a 90-percent confidence level, were as follows.

Unpainted/As-received	**404,423 - 512,836 cycles**
Chemically Stripped	**517,897 - 703,990 cycles**
High-Pressure Water	**434,621 - 635,350 cycles**

b. For the 7075-T6 alclad tests, a large data spread occurred for all conditions; and for the chemically and high-pressure waterjet stripped coupons, a large number of test run-outs occurred at 750,000 cycles. For example:

The minimum and maximum values for the fatigue life of the unpainted/as-received coupons were 301,410 and 725,915 cycles, respectively, giving a range of 424,505 cycles.

The minimum and maximum values for the high-pressure waterjet process were 175,595 and 750,000 cycles, respectively, giving a range of 574,405 cycles. Six run-outs occurred for the 14 tests. (Two very low data points, which deviated significantly from the data distribution, were also found, indicating that the data points may have been the results of a premature coupon failure.)

The minimum and maximum values for the chemical stripping process were 426,945 and 750,000 cycles, respectively, giving a range of 323,055 cycles. Four run-outs occurred for the nine tests.

c. Because of the wide data range and large number of run-out tests, the results of the statistical analysis were significantly affected. The analysis showed a difference in the unpainted/as-received coupons after processing. For both processes, the fatigue life was higher than that of the unpainted/as-received coupons. This behavior was not observed in any of the previous tests. Because the results of the statistical analysis may not produce a valid comparison when the run-out conditions are included, two cases were evaluated:

Case 1 - **statistical analysis of all conditions, including all data points.**

Case 2 - **statistical analysis of all conditions, excluding all data run-outs and two very low data points for the high-pressure waterjet process.**

d. For Case 1, the cycles to failure for each test condition, at a 90-percent confidence level, are in paragraph 4.10.2.3.a. A statistical comparison of the fatigue data showed that the fatigue lives of the chemical and high-pressure waterjet processes are roughly the same. However, both processes have higher fatigue lives when compared to the unpainted/as-received condition, and the difference is significant.

e. The statistical data distribution in Figure 50 raises two issues. The first is the large number of data run-outs for the chemically and the high-pressure-waterjet stripped coupons. The second issue is the two very low data points for the high-pressure waterjet coupons. There are presently no explanations for the large number of data run-outs compared to the unpainted/as-received coupons. No work was planned within the scope of the study to investigate the behavior of run-outs; only the effect is noted. The two low data points for the high-pressure waterjet-processed coupons deviate significantly from the data distribution, indicating that something occurred to produce premature failure. This behavior could be related to a coupon surface defect, which acted as a stress user to produce failure.

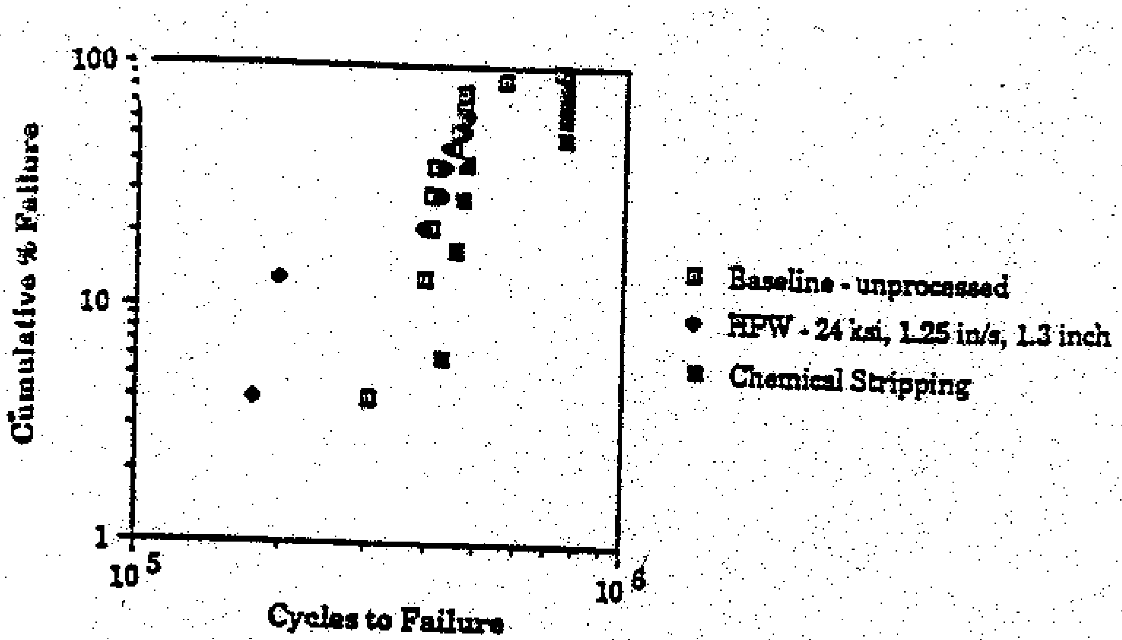


Figure 50. Statistical logarithmic data distribution for 7075-T6 alclad, 500,000 cycles (case 1).

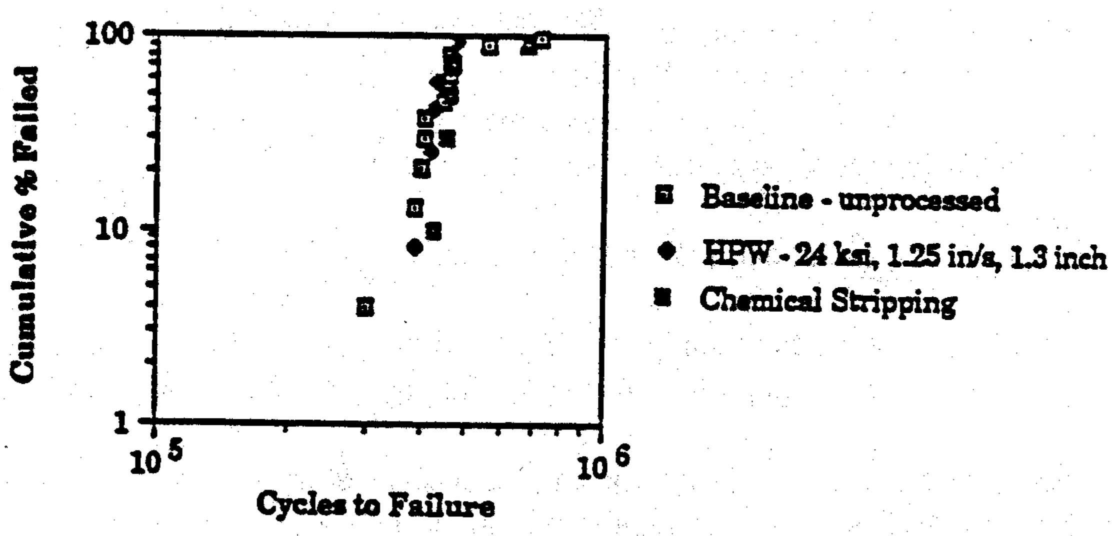


Figure 51. Statistical logarithmic data distribution for 7075-T6 alclad, 500,000 cycles (case 2).

f. For Case 2, the cycles to failure for each test condition, at a 90-percent confidence level, were as follows.

Unpainted/As-received	**404,423 - 512,836 cycles**
Chemically Stripped	**408,479 - 590,885 cycles**
High-Pressure Water	**408,870 - 463,325 cycles**

g. The fatigue lives of the three test conditions were not statistically different from one another. The statistical data distribution for Case 2 in Figure 51 shows that the behavior of the sample populations was similar to the behavior observed for the 100,000 cycle tests. The effects of the artificial aging process on 7075-T6 coupons, as documented for the 2024-T3 coupons for 100,000 and 500,000 cycle tests, are not observed. The absence of any effect is related to the artificial aging temperature being less than the precipitation-heat-treatment temperature. Typically, 7075-T6 coupons are solution heat treated at 900° F, followed by a precipitation heat treatment at 250° F for 24 hours. Since the artificial aging temperature is less than the precipitation heat treatment temperature, the microstructure resulting from the precipitation heat treatment is stable and unchanged by the artificial aging temperature. Consequently, the fatigue life for chemically and high-pressure-waterjet processed data compared to the unpainted/as-received data shows no significant changes in Case 2.

4.10.2.4 Al 7075-T6 Bare.

a. High-pressure waterjet and chemically stripped coupons were tested for the maximum stress required to produce failure in 500,000 cycles for the unpainted/as-received 7075-T6 bare coupons. The cycles to failure for each test condition, at a 90-percent confidence level, were calculated. Then coupons stripped by the two methods were compared to unpainted/as-received coupons to determine if there were statistical differences in the data. The cycles to failure for each test condition, at a 90-percent confidence level, were as follows.

Unpainted/As-received	**435,674 - 677,396 cycles**
Chemically Stripped	**95,947 - 361,620 cycles**
High-Pressure Water	**495,462 - 729,505 cycles**

b. A large data spread occurred for all 7075-T6 bare test conditions. For example:

- **Minimum and maximum fatigue life values of the unpainted/as-received coupons were 127,424 and 750,000 cycles, respectively, giving a range of 622,576 cycles. Five run-outs occurred for the 12 tests.**

- **Minimum and maximum values for the chemical stripping process were 40,914 and 597,672 cycles, respectively, giving a range of 556,758 cycles. No run-outs occurred for the eight tests.**

- **Minimum and maximum values for the high-pressure waterjet process were 175,680 and 750,000 cycles, respectively, giving a range of 574,320 cycles. Nine run-outs occurred for the 13 tests.**

d. Because of the wide data range and large number, the run-out tests for the unpainted/as-received coupons and high-pressure waterjet process resulted in no statistical differences in the data.

e. Figure 52 shows the statistical data distribution, which includes the effects of the run-out tests and the large data spread for the chemically stripped coupons. Figure 52 also

shows that the chemical stripping process has significantly reduced the fatigue behavior of 7075-T6 bare. The mechanism for this reduction is not presently known. The fatigue life for the high-pressure-waterjet-processed coupons does not appear to be significantly different from the baseline/as-received coupons.

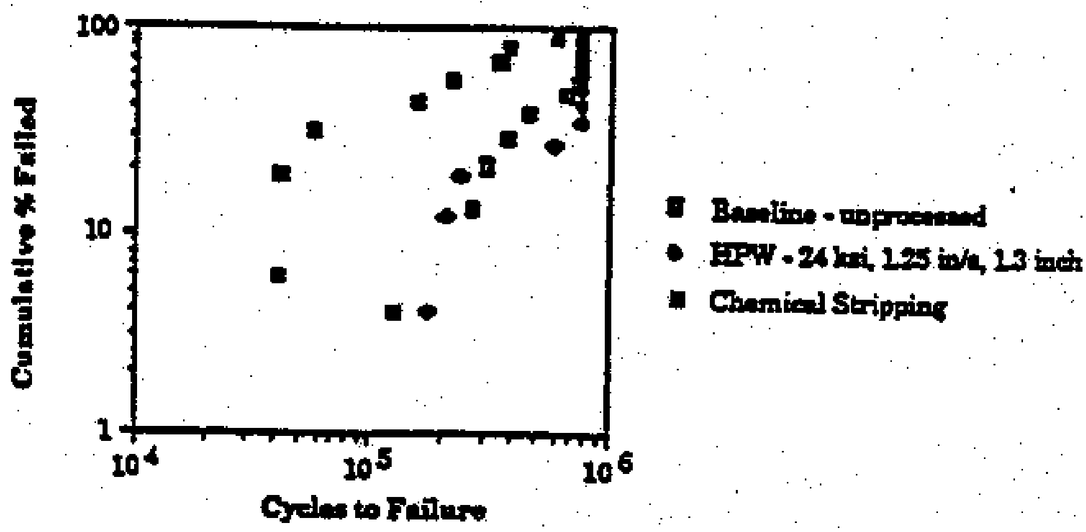


Figure 52. Statistical logarithmic data distribution for 7075-T6 bare, 500,000 cycles

4.10.3 Fatigue Notched Front and Back, Test Results.

These tests will be performed at a later date using coupons notched by OC-ALC and prepared by USBI.

4.10.4 FCGR Test Results.

The results of the FCGR tests for each metal over the DK range of 6 ksi-in$^{1/2}$ to 15 ksi-in$^{1/2}$ follow.

4.10.4.1 Al 2024-T3 alclad.

a. Figure 53 presents the FCGR as a function of the stress intensity factor. The FCGR data for the unpainted/unprocessed coupons, chemically stripped coupons, and high-pressure-waterjet-processed coupons follows.

DK (ksi-in$^{1/2}$)	Unpainted/As-received (inch/cycle)	Chemical Stripping (inch/cycle)	High-Pressure Water (inch/cycle)
7	8.36947e-7	9.46273e-7	1.05988e-6
8	1.40948e-6		1.536373-6
9	1.85053e-6	1.9503e-6	2.017873-6

11	**3.39682e-6**	**3.17341e-6**	**3.41882e-6**
12	**4.32120e-6**	**4.27893e-6**	**4.20408e-6**
13	**5.504083-6**	**5.13217e-6**	**5.576446e-6**
14	**6.81213e-6**	**6.36058e-6**	**6.99411e-6**
15	**8.63405e-6**	**8.25728e-6**	**8.66124e-6**

The FCGR is higher for the high-pressure waterjet coupons than it is for the unpainted/unprocessed coupons. This difference, believed to be related to a stress intensity threshold phenomena, was not considered detrimental to the material.

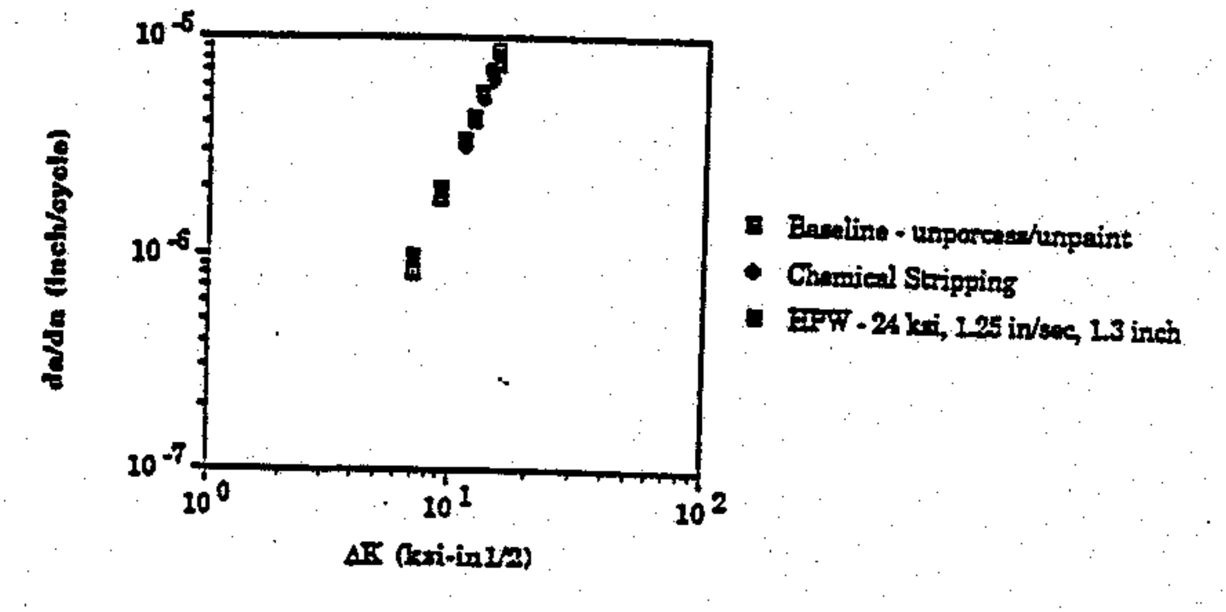


Figure 53. FCGR as a function of the stress intensity factor, 2024-T3 alclad.

b. A statistical comparison of the data was performed over the DK range to determine if any difference existed between the unpainted/unprocessed and chemically stripped coupons, the unpainted/unprocessed and high-pressure waterjet-processed coupons, and the chemically stripped and high-pressure waterjet coupons. Based on the analysis, the FCGR behavior showed the following:

- **DK = 7 ksi-in$^{1/2}$**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

- **DK = 8 ksi-in$^{1/2}$**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **DK = 9 ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **DK = 11 ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

    - **DK = 12 ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

    - **DK = 13 ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

    - **DK = 14 ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

  - **The FCGR of the high-pressure waterjet coupons is approximately 9 percent greater than the chemically stripped coupons.**

- DK = 15 ksi-in$^{1/2}$

  - There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.

  - There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.

c. In summary, for the 2024-T3 clad high-pressure waterjet process at 24,000 psi, 1.25-inch/second travel rate, and 1.3-inch standoff, the FCGR is not affected when compared to unpainted/unprocessed or chemically stripped coupons for all DK values except at 7 and 14 ksi-in$^{1/2}$.

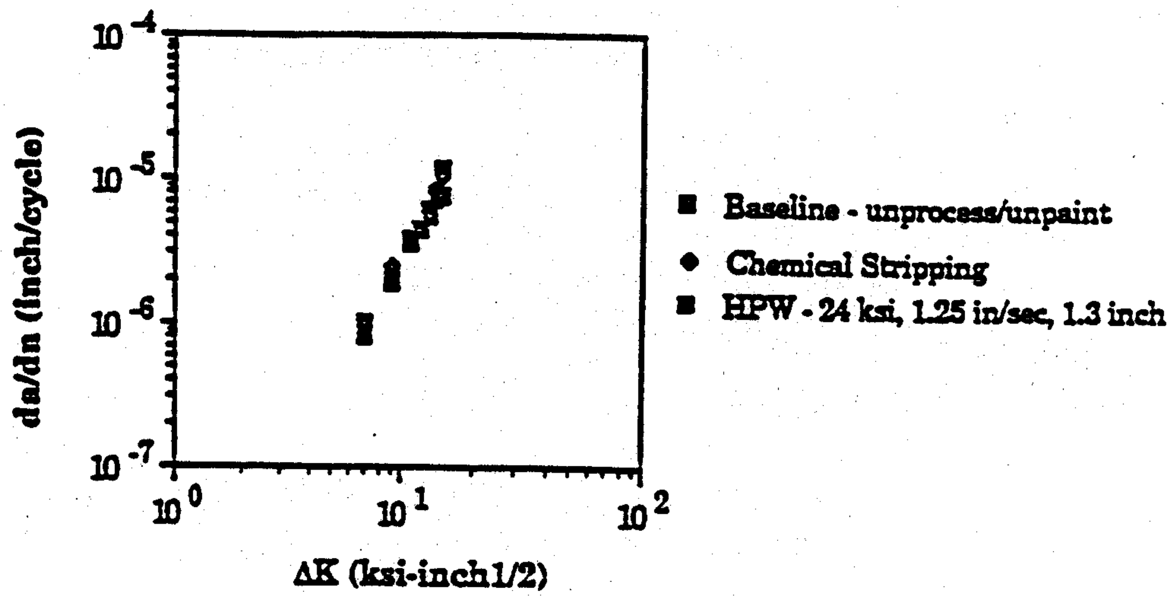


Figure 54. FCGR as a function of the stress intensity factor, 2024-T3 bare.

4.10.4.2 Al 2024-T3 Bare.

a. Figure 54 presents the FCGR as a function of the stress intensity factor. The FCGR data for unpainted/unprocessed, chemically stripped, and high-pressure waterjet-processed coupons follows.

DK (ksi-in$^{1/2}$)	Unpainted/As-received (inch/cycle)	Chemical Stripping (inch/cycle)	High-Pressure Water (inch/cycle)
7	1.02687e-7	9.46273e-7	8.15250e-7
8	1.57540e-6	1.48775e-6	
9	2.05877e-6	2.42914e-6	1.89680e-6
11	3.77153e-6	3.17341e-6	3.55875e-6
12	4.47129e-6	4.59508e-6	4.59311e-6

13	**6.04513e-6**	**5.98215e-6**	**5.58869e-6**
14	**7.08646e-6**	**8.57441e-6**	**7.08011e-6**
15	**1.17011e-5**	**8.25728e-6**	**7.45213e-6**

b. A statistical comparison of the data was performed over the DK range to determine if any difference existed between the unpainted/unprocessed and chemically stripped coupons, the unpainted/unprocessed and the high-pressure waterjet-processed coupons, and the chemically stripped and the high-pressure waterjet coupons. Based on the analysis, the FCGR behavior showed the following:

- **DK = 7 ksi-in$^{1/2}$**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**
  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**
- **DK = 8 ksi-in$^{1/2}$**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**
- **DK = 9 ksi-in$^{1/2}$**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**
  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**
- **DK = 11 ksi-in$^{1/2}$**
  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped**

coupons.

- There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.

- There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.

■ Δ**K = 12 ksi-in$^{1/2}$**

- There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.

- There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.

- There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.

■ Δ**K = 13 ksi-in$^{1/2}$**

- There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.

- There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.

- There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.

■ Δ**K = 14 ksi-in$^{1/2}$**

- There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.

- There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.

- There is no statistical difference between the chemically stripped

coupons and the high-pressure waterjet coupons.

- **DK = 15 ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

c. In summary, for the 2024-T3 bare high-pressure waterjet process at 24,000 psi, 1.25- inch/second travel rate, and 1.3-inch standoff, the FCGR is not affected when compared to the unpainted/unprocessed or chemically stripped coupons.

4.10.4.3 Al 7075-T6 Alclad.

a. Figure 55 presents FCGR as a function of the stress intensity factor. The FCGR data for unpainted/unprocessed, chemically stripped, and high-pressure-waterjet-processed coupons follows.

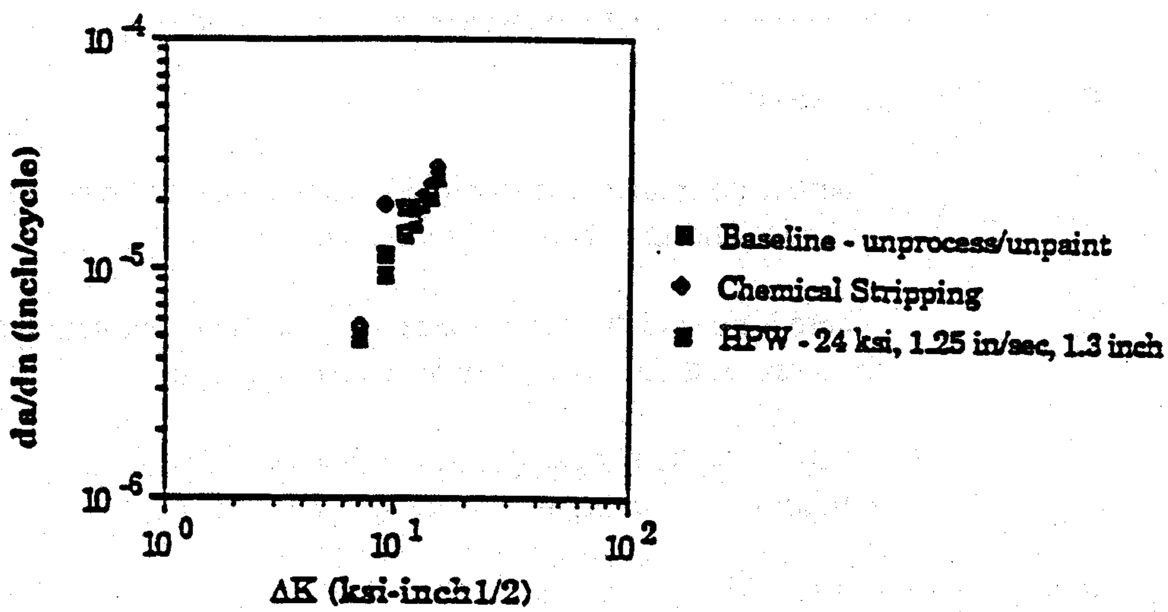


Figure 55. FCGR as a function of the stress intensity factor, 7075-T6 alclad.

DK	Unpainted/As-received	Chemical Stripping	High-Pressure Water

$(ksi\text{-}in^{1/2})$	(inch/cycle)	(inch/cycle)	(inch/cycle)
7	**5.21159e-6**	**5.54325e-6**	**4.99270e-6**
8	**6.85000e-6**		**7.42000e-6**
9	**1.14281e-5**	**1.18883e-5**	**9.48296e-6**
11	**1.42576e-5**	**1.45371e-5**	**1.83000e-5**
12	**1.56167e-5**	**1.77917e-5**	**1.64731e-5**
13	**1.88937e-5**	**2.02820e-5**	**1.89095e-5**
14	**2.03508e-5**	**2.02820e-5**	**2.19271e-5**
15	**2.51738e-5**	**2.76115e-5**	**2.56000e-5**

b. A statistical comparison of the data was performed over the ΔK range to determine if any difference existed between the unpainted/unprocessed and chemically stripped coupons, the unpainted/unprocessed and high-pressure-waterjet-processed coupons, and the chemically stripped and high-pressure waterjet coupons. Based on the analysis, the FCGR behavior showed the following:

- **$\Delta K = 7$ ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

- **$\Delta K = 8$ ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **$\Delta K = 9$ ksi-in$^{1/2}$**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

  - **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **$\Delta K = 11$ ksi-in$^{1/2}$**

- **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

- **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **$\Delta K = 12$ ksi-in$^{1/2}$**

- **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

- **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **$\Delta K = 13$ ksi-in$^{1/2}$**

- **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

- **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **$\Delta K = 14$ ksi-in$^{1/2}$**

- **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped**

coupons.

- **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **ΔK = 15 ksi-in$^{1/2}$**

- **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

- **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

c. In summary, for the 7075-T6 clad high-pressure waterjet process at 24,000 psi, 1.25- inch/second travel rate, and 1.3-inch standoff, FCGR is not affected when compared to the unpainted/unprocessed or the chemically stripped coupons.

4.10.4.4 Al 7075-T6 Bare.

a. Figure 56 presents FCGR as a function of the stress intensity factor. The FCGR data for the unpainted/unprocessed, chemically stripped, and high-pressure-waterjet-processed coupons follows.

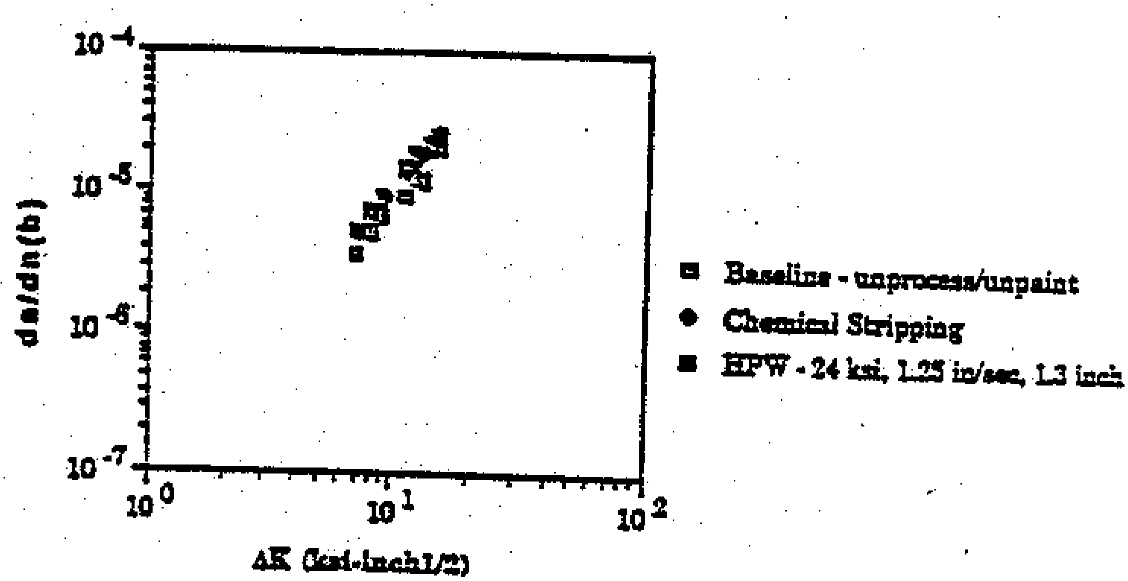


Figure 56. FCGR as a function of the stress intensity factor, 7075-T6 bare

DK (ksi-in$^{1/2}$)	Unpainted/As-received (inch/cycle)	Chemical Stripping (inch/cycle)	High-Pressure Water (inch/cycle)
7	3.55773e-6	5.54325e-6	5.24200e-6
8	5.20700e-6		7.33000e-6
9	6.99965e-6	9.07496e-5	9.44896e-6
11	9.20813e-6	1.45371e-5	1.451003-5
12	1.25474e-5	1.64063e-5	1.92474e-5
13	1.40377e-5	1.89196e-5	1.87416e-5
14	2.21447e-5	2.27767e-5	2.13955e-5
15	2.00500e-5	2.76155e-5	2.39500e-5

b. A statistical comparison of the data was performed over the DK range to determine if any difference existed between the unpainted/unprocessed and chemically stripped coupons, the unpainted/unprocessed and the high-pressure-waterjet-processed coupons, and the chemically stripped and the high-pressure waterjet coupons. Based on the analysis, the FCGR behavior showed the following:

- **DK = 7 ksi-in$^{1/2}$**

  - **The fatigue crack growth rate for the chemically stripped coupons is greater than for the unpainted/unprocessed coupons.**

  - **The fatigue crack growth rate for the high-pressure waterjet coupons is greater than for the unpainted/unprocessed coupons.**

  - **There is no statistical difference between the chemically stripped**

coupons and the high-pressure waterjet coupons.

- **DK = 8 ksi-in$^{1/2}$**

  - **The fatigue crack growth rate for the high-pressure waterjet coupons is greater than for the unpainted/unprocessed coupons.**

- **DK = 9 ksi-in$^{1/2}$**

  - **The fatigue crack growth rate for the chemically stripped coupons is greater than for the unpainted/unprocessed coupons.**

  - **The fatigue crack growth rate for the high-pressure waterjet coupons is greater than for the unpainted/unprocessed coupons.**

  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

- **DK = 11 ksi-in$^{1/2}$**

  - **The fatigue crack growth rate for the chemically stripped coupons is greater than for the unpainted/unprocessed coupons.**

  - **The fatigue crack growth rate for the high-pressure waterjet coupons is greater than for the unpainted/unprocessed coupons.**

  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

- **DK = 12 ksi-in$^{1/2}$**

  - **The fatigue crack growth rate for the chemically stripped coupons is greater than for the unpainted/unprocessed coupons.**

  - **The fatigue crack growth rate for the high-pressure waterjet coupons is greater than for the unpainted/unprocessed coupons.**

  - **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

- **DK = 13 ksi-in$^{1/2}$**

  - **The fatigue crack growth rate for the chemically stripped coupons is greater than for the unpainted/unprocessed coupons.**

  - **The fatigue crack growth rate for the high-pressure waterjet**

coupons is greater than for the unpainted/unprocessed coupons.

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **ΔK = 14 ksi-in$^{1/2}$**

- **There is no statistical difference between the unpainted/unprocessed coupons and the chemically stripped coupons.**

- **There is no statistical difference between the unpainted/unprocessed coupons and the high-pressure waterjet coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

■ **ΔK = 15 ksi-in$^{1/2}$**

- **The fatigue crack growth rate for the chemically stripped coupons is greater than for the unpainted/unprocessed coupons.**

- **The fatigue crack growth rate for the high-pressure waterjet coupons is greater than for the unpainted/unprocessed coupons.**

- **There is no statistical difference between the chemically stripped coupons and the high-pressure waterjet coupons.**

c. In summary, for the 7075-T6 bare chemically stripped coupons and high-pressure waterjet coupons processed at 24,000 psi, 1.25-inch/second travel rate, and 1.3-inch standoff, the FCGR is statistically different when compared to the unpainted/unprocessed coupons for all ΔK values except 14 ksi-inch$^{1/2}$. Because there is no statistical difference between the high-pressure waterjet coupons and the chemically stripped coupons, there may be a problem with the data for the unpainted/unprocessed coupons that would cause a statistical difference to appear. Because the high-pressure waterjet coupons and the chemically stripped coupons do not show a difference, the high-pressure waterjet process does not detrimentally affect the FCGR for 7075-T6 bare.

4.10.5 Corrosion Evaluation Test Results.

The following paragraphs present the results of the corrosion testing.

4.10.5.1 Al 2024-T3 Alclad.

a. Figure 57 shows the effect of the salt fog exposure on the weight change. The

greatest change in the weight occurred for the unpainted condition. The weight changes after painting, painting/processing, and painting/processing/scribing were very small. Based on weight changes, the processing did not significantly effect the corrosion behavior.

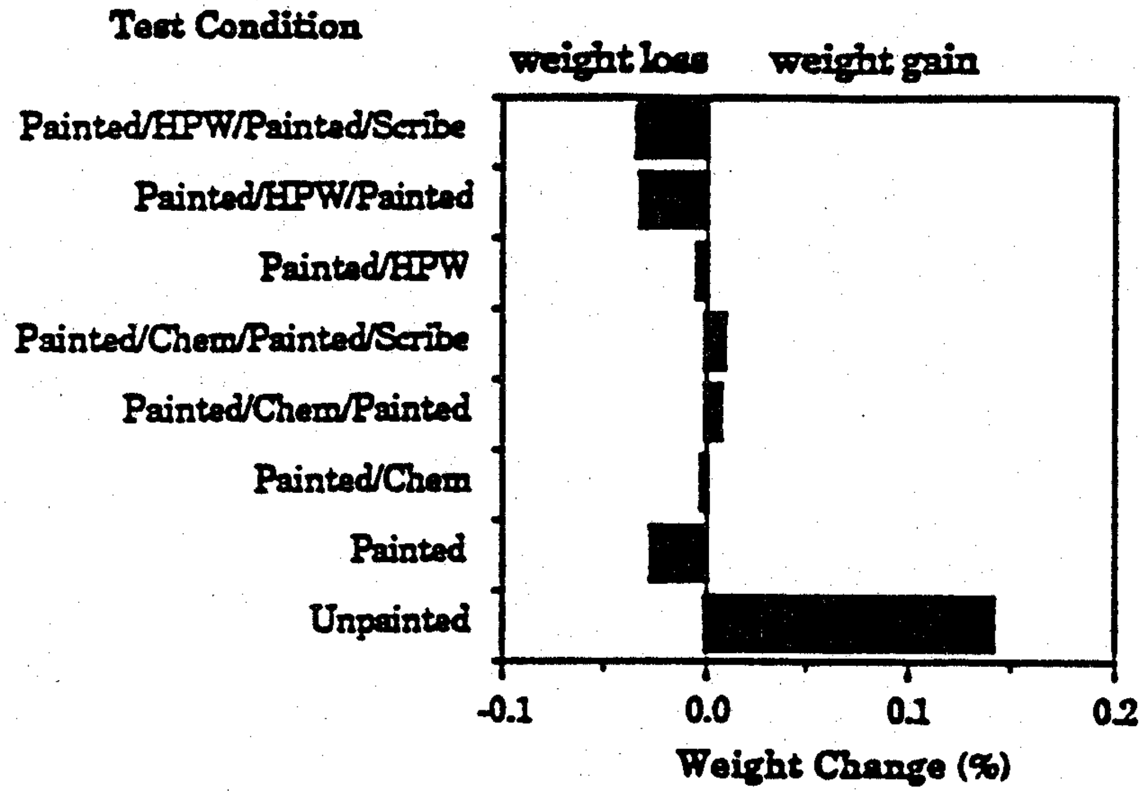


Figure 57. Corrosion results for 2024-T3 alclad.

b. Figure 58 summarizes observances at 10-, 20- and 30-day exposures and values for the weight change for each coupon configuration. The high-pressure waterjet process and the chemical stripping process did not significantly impact the observed corrosion behavior when compared to the painted coupons.

Coupon Configuration	Average Weight Change (%)	Visual Observations
• Unpainted	0.142	10 days: surface slightly darkened; salt fog runoff pattern seen 20 days: no difference compared to 10 day exposure 30 days: very small pits formed in streaked areas
• Painted	-0.026	10 days: no change observed 20 days: no change observed 30 days: no change observed
• Painted/Chemically Stripped	-0.002	10 days: no change observed 20 days: no change observed 30 days: no significant change except for development of two slight streaks on two panels
• Painted/Chemically Stripped/ Painted	0.007	10 days: no change observed 20 days: no change observed 30 days: no change observed
• Painted/Chemically Stripped/ Painted/Scribed	0.008	10 days: white corrosion products and white streaks developed along scribe 20 days: corrosion continued 30 days: no change from twenty day
• Painted/HPW	-0.003	10 days: no change observed 20 days: no change observed 30 days: small amount of white spots formed on one panel. two panels developed fine white crystalline coating
• Painted/HPW/Painted	-0.031	10 days: no change observed 20 days: no change observed 30 days: no change observed in two panels. one panel developed slight white streak along edge
• Painted/HPW/Painted/Scribe	-0.033	10 days: slight amount of white corrosion product developing along scribe. 20 days: more corrosion developing along scribe 30 days: no change observed in two panels. white corrosion continued in one panel

Figure 58. Weight change and visual observations for 2024-T3 alclad

after salt fog exposure.

4.10.5.2 Al 2024-T3 Bare.

a. Figure 59 shows the effect of the salt fog exposure on the weight change. The greatest weight change occurred for the unpainted condition. The amount of weight gain after exposure for 2024-T3 bare was significantly larger than for 2024-T3 clad due to no protective layer for corrosion protection. The large gain in weight for the painted coupons resulted because corrosion formed on the unpainted sides of the coupons. The weight changes after painting, painting/processing, and painting/processing/scribing were small compared to the unpainted coupons.

b. The largest change in weight occurred for the chemically stripped coupons. Based on weight changes, the high-pressure waterjet process did not significantly affect corrosion behavior.

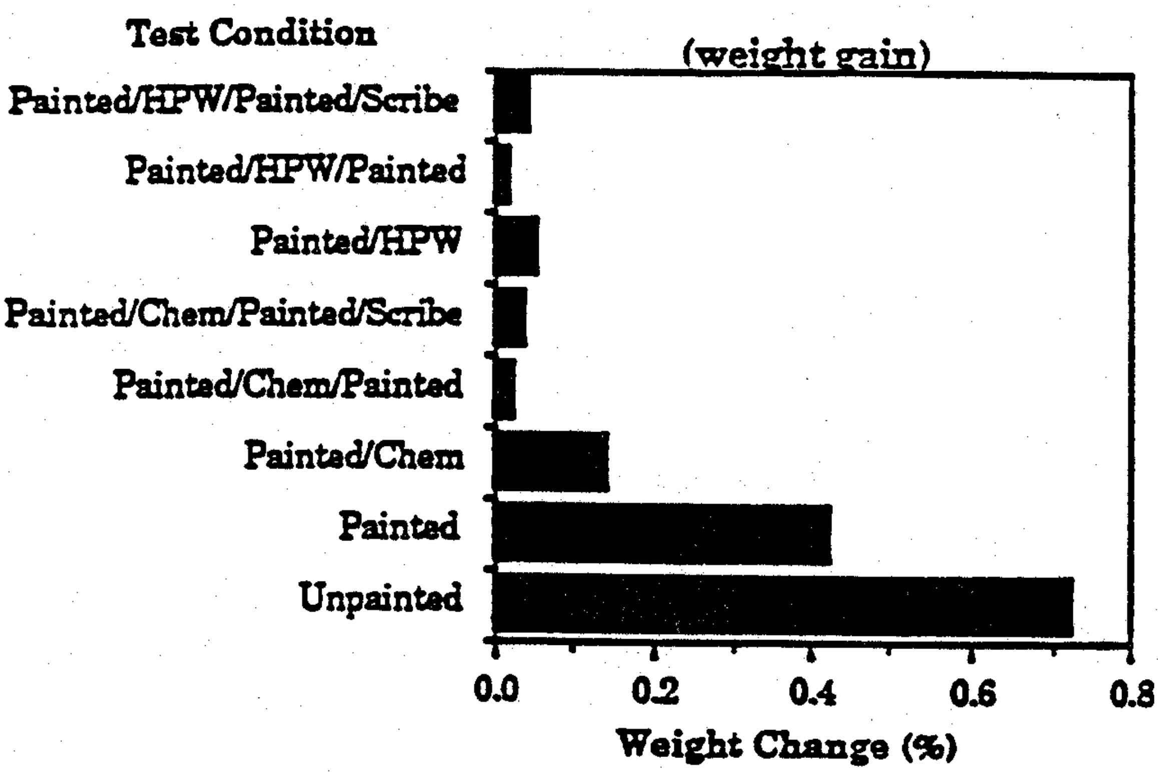


Figure 59. Corrosion results for 2024-T3 bare.

c. Figure 60 summarizes observations at 10-, 20-, and 30-day exposures and values for the weight change for each coupon configuration. The unpainted and painted coupons showed the largest weight gain. The chemically stripped coupons showed a greater weight gain than did the high-pressure waterjet coupons. The painted/stripped/painted coupons and

the painted/processed/painted/scribed coupons showed very small weight gains.

Coupon Configuration	Average Weight Change (%)		Visual Observations
• Unpainted	0.725	10 days:	heavy coat of white corrosion products. red spots random on surface. corrosion pits
		20 days:	deepening of corrosion pits
		30 days:	corrosion pits almost penetrated surface
• Painted	0.426	10 days:	no change observed
		20 days:	no change observed
		30 days:	no change observed
• Painted/Chemically Stripped	0.143	10 days:	light corrosion (white streaks)
		20 days:	small corrosion pits
		30 days:	deepening of corrosion pits
• Painted/Chemically Stripped/ Painted	0.024	10 days:	no change observed
		20 days:	blistering of paint
		30 days:	no change from 20 day exposure
• Painted/Chemically Stripped/ Painted/Scribed	0.039	10 days:	white streaks developing along scribe
		20 days:	increase in size of white
		streaks.	cracking of paint along scribe
		30 days:	no change from twenty day
• Painted/HPW	0.055	10 days:	no change observed
		20 days:	no change observed
		30 days:	small amount of white streaks formed on two panels. developed fine white crystalline coating
• Painted/HPW/Painted	0.018	10 days:	no change observed
		20 days:	slight streaks formed. very fine cracks in paint
		30 days:	small blisters formed in paint. streaks became worse.
• Painted/HPW/Painted/Scribe	0.046	10 days:	slight amount of white corrosion product developing along scribe.
		20 days:	more corrosion developing along scribe
		30 days:	condition worsened with cracked appearance forming on paint.

Figure 60. Weight change and visual observations for 2024-T3 bare after salt fog exposure.

4.10.5.3 Al 7075-T6 Alclad.

a. Figure 61 shows the effect of the salt fog exposure on the weight change. The greatest weight change occurred for the unpainted condition. The weight changes after painting, painting/processing, and painting/processing/scribing were very small. Based on weight changes, the high-pressure waterjet process did not significantly affect the corrosion behavior of the 7075-T6 clad compared to chemical stripping.

b. Figure 62 summarizes observations after 10-, 20-, and 30-day exposures and values for the weight change for each coupon configuration. The unpainted and painted/chemically stripped/painted coupons showed the largest weight gain. The weight change for the latter coupon configuration occurred because corrosion formed on the unpainted sides of the coupons.

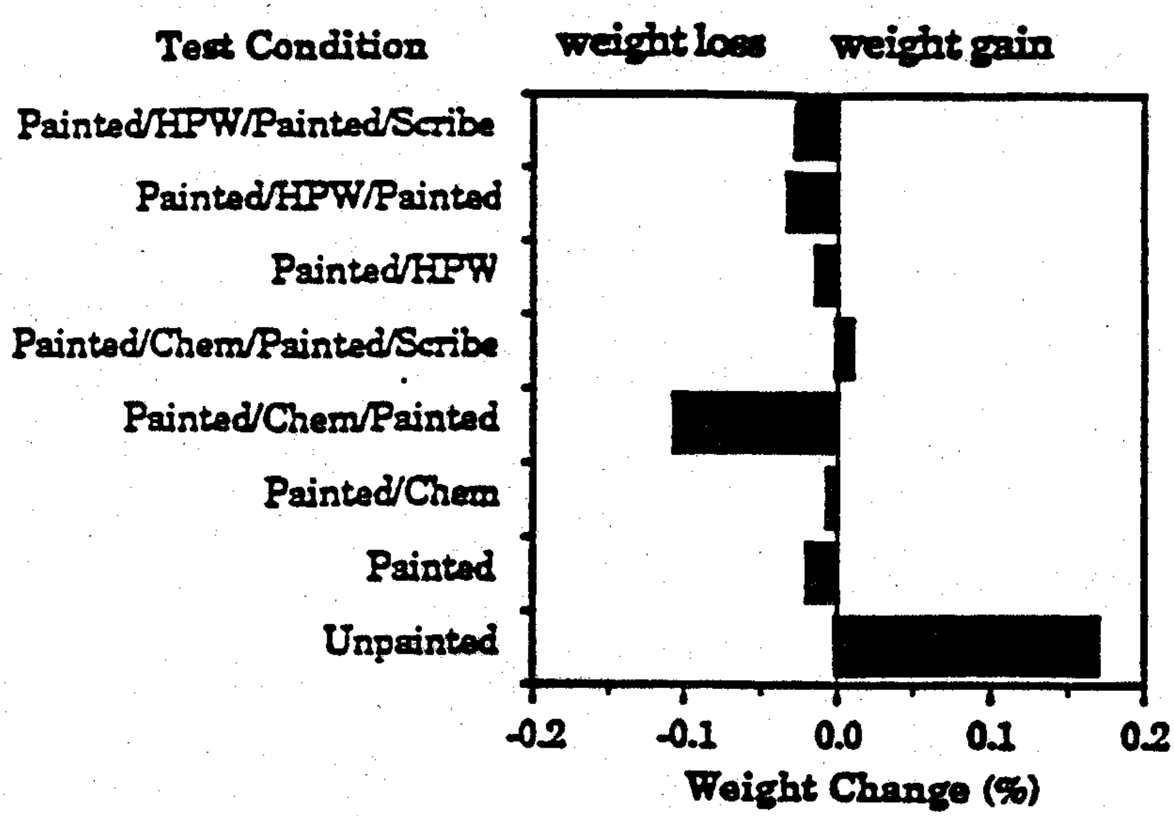


Figure 61. Corrosion results for 7075-T6 alclad.

Coupon Configuration	Average Weight Change (%)	Visual Observations
• Unpainted	0.171	10 days: some white streaks formed 20 days: small corrosion pits formed 30 days: no change from 20 day exposure
• Painted	-0.024	10 days: no change observed 20 days: no change observed 30 days: no change observed
• Painted/Chemically Stripped	-0.004	10 days: no change observed 20 days: no change observed 30 days: no change observed
• Painted/Chemically Stripped/ Painted	-0.105	10 days: no change observed 20 days: no change observed 30 days: no change observed
• Painted/Chemically Stripped/ Painted/Scribed	0.011	10 days: slight darkening along scribe 20 days: no change compared to 10 day exposure 30 days: two panels developed small white streaks along scribe marks
• Painted/HPW	-0.014	10 days: no change observed 20 days: no change observed 30 days: thin coat if white corrosion observed over coupon surface
• Painted/HPW/Painted	-0.031	10 days: no change observed except one panel developed two small blisters 20 days: blisters bled white corrosion products 30 days: no change from twenty day exposure
• Painted/HPW/Painted/Scribe	-0.026	10 days: slight amount of white corrosion product developing along scribe. 20 days: more corrosion developing along scribe 30 days: small red rust spot observed on two panels after drying

Figure 62. Weight change and visual observations for 7075-T6 alclad after salt fog exposure.

4.10.5.4 Al 7075-T6 Bare.

a. Figure 63 shows the effect of the salt fog exposure on the weight change. The greatest weight change occurred for the unpainted condition. The weight changes after painting, painting/processing, and painting/processing/scribing were very small. Based on weight changes, the high-pressure waterjet process did not significantly affect the corrosion behavior of the 7075-T6 bare compared to chemical stripping.

b. Figure 64 summarizes observations after 10-, 20-, and 30-day exposures and values for the weight change for each coupon configuration. All coupon configurations except unpainted showed very small changes in weight after a 30-day exposure to the salt fog. Based on the test results, the high-pressure waterjet process did not significantly affect the corrosion behavior of 7075-T6 bare compared to chemical stripping.

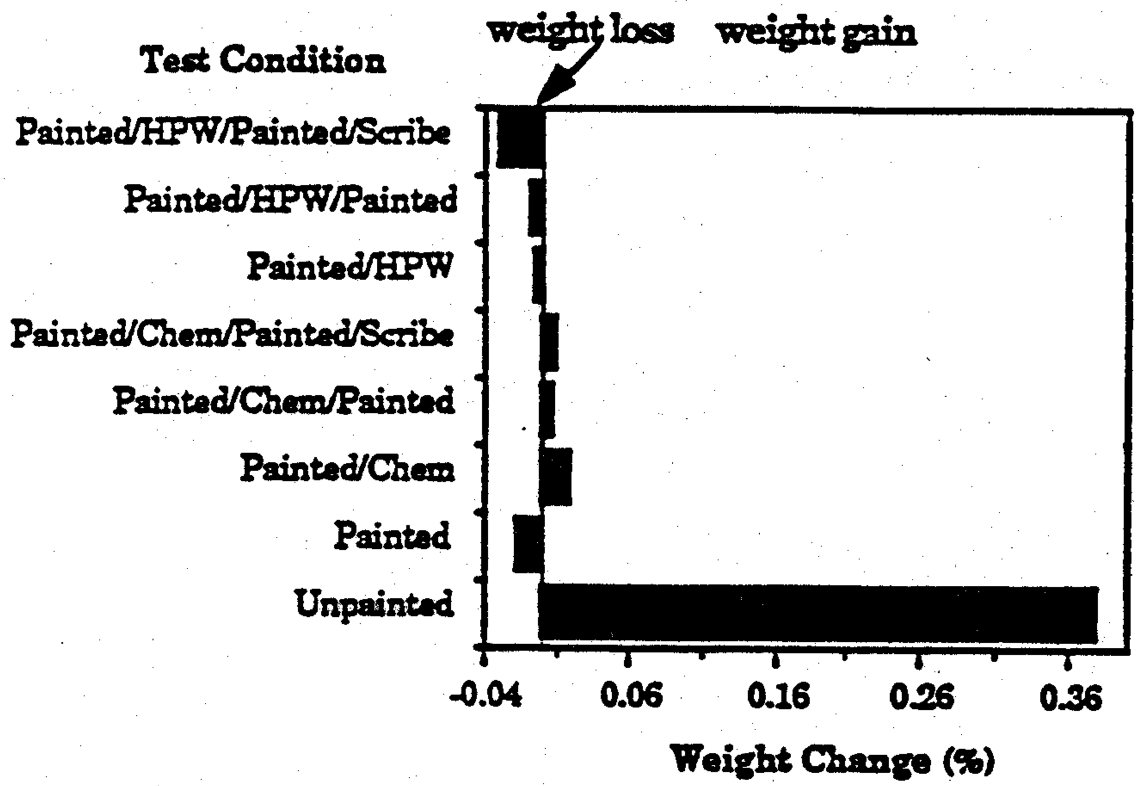


Figure 63. Corrosion results for 7075-T6 bare.

Coupon Configuration	Average Weight Change (%)	Visual Observations
• Unpainted	0.380	10 days: formation of heavy layer of white corrosion products 20 days: corrosion pits formed 30 days: corrosion pits deepened and almost penetrated the metal
• Painted	-0.024	10 days: no change observed 20 days: no change observed 30 days: no change observed. weight loss occurred due to small amount of corrosion on back of coupon
• Painted/Chemically Stripped	0.020	10 days: several dark streaks formed. some white corrosion products in center of panel 20 days: no change from 10 day exposure 30 days: no change observed from 10 day exposure
• Painted/Chemically Stripped/ Painted	0.007	10 days: small amount of corrosion on edge of coupon 20 days: white streaks on back of coupon observed 30 days: no change from 20 day exposure
• Painted/Chemically Stripped/ Painted/Scribed	0.012	10 days: dark streaks along scribe 20 days: no change from 10 day exposure 30 days: no change from 20 day exposure
• Painted/HPW	-0.004	10 days: no change observed 20 days: no change observed 30 days: thin coat if white corrosion observed over coupon surface
• Painted/HPW/Painted	-0.007	10 days: no change observed 20 days: no change observed 30 days: no change observed
• Painted/HPW/Painted/Scribe	-0.031	10 days: slight amount of white corrosion product developing along scribe. 20 days: more corrosion developing along scribe 30 days: no change observed

Figure 64. Weight change and visual observations for 7075-T6 bare after salt fog exposure.

4.10.6 Spot Weld Integrity Test Results.

The following paragraphs discuss the results of the eddy current inspection of spot welded panels.

4.10.6.1 Flat Panels.

a. Al 2024-T3 alclad, 0.032-inch test panels were inspected after painting but before processing to establish the baseline. Two areas had broken or cracked spot welds where the pitch was 1.0 inch. Figure 65 shows spot welds as black boxes. After high-pressure waterjet processing, no additional spot welds were broken or cracked.

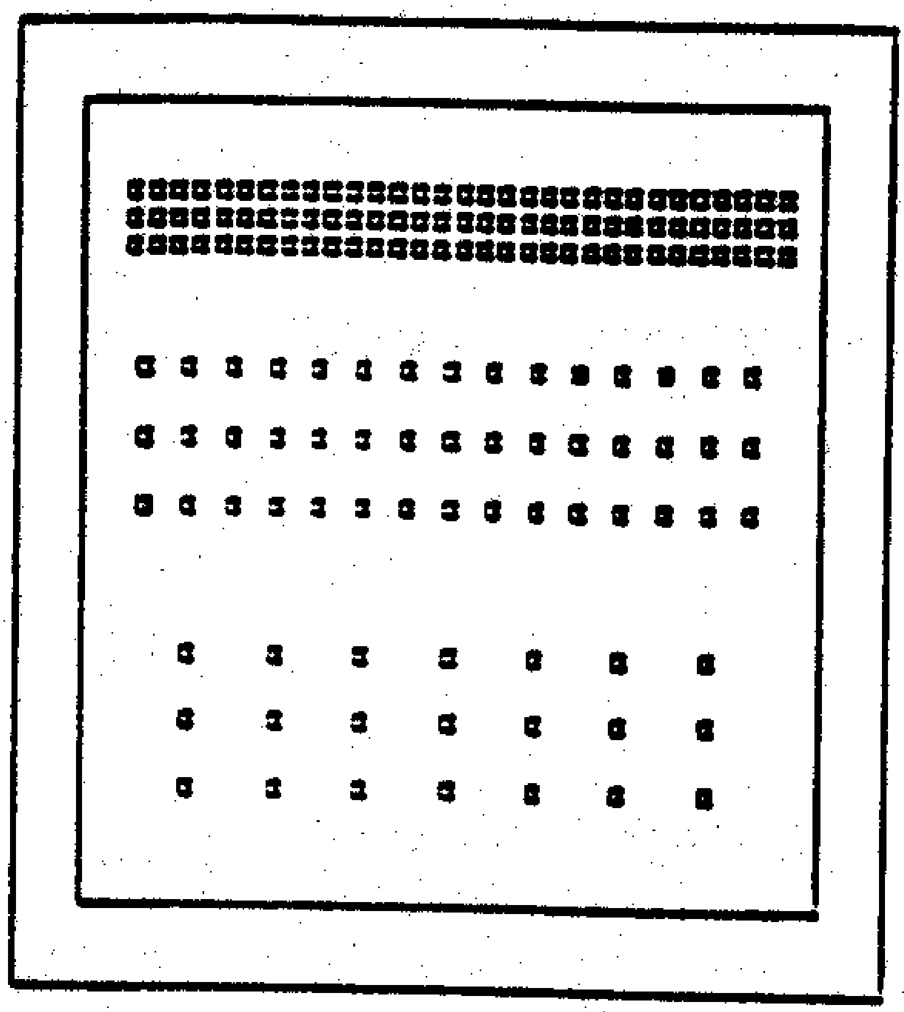


Figure 65. Baseline for flat spot weld panel: 2024-T3 alclad, 0.032-inch.

b. Al 2024-T3 alclad, 0.080-inch test panels were inspected after painting but before processing to establish the baseline. Three areas had broken or cracked spot welds where the

pitch was 0.25 inch. Figure 66 shows these spot welds as black boxes. After high-pressure waterjet processing, no additional spot welds were broken or cracked.

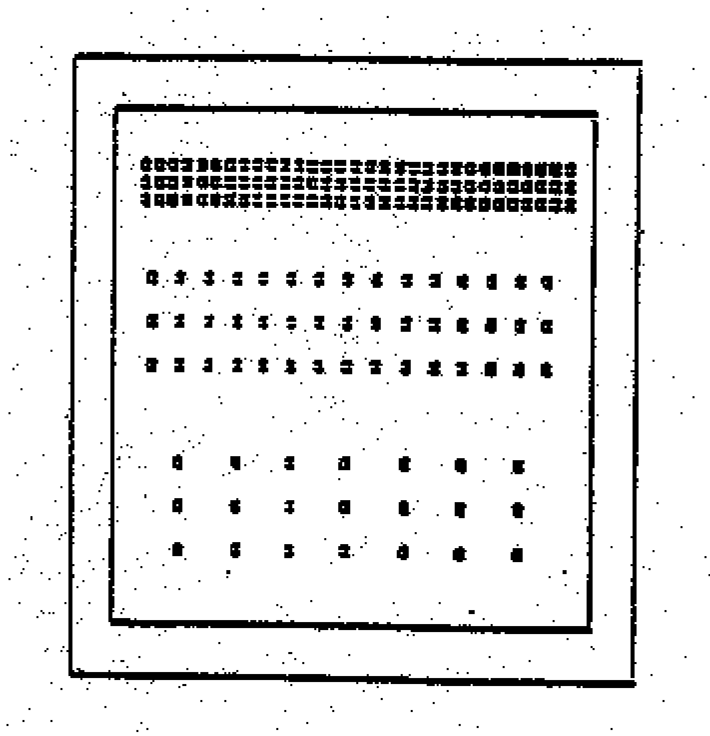


Figure 66. Baseline for spot weld panel: 2424-T3 alclad, 0.080-inch.

c. Al 7075-T6 alclad, 0.032-inch test panels were inspected after painting but before processing to establish the baseline. No broken or cracked spot welds were found for the pre-process and post-process condition.

d. Al 7075-T6 alclad, 0.080-inch test panels were inspected after painting but before processing to establish the baseline. No broken or cracked spot welds were found for the pre-process and post-process condition.

4.10.6.2 Bent Panels.

a. Al 2024-T3 alclad, 0.032-inch test panels were inspected after painting but before processing to establish the baseline. Twelve areas had broken or cracked spot welds where the pitch was 1.0 inch. Three areas had a broken or cracked spot-weld where the pitch was 0.5 inch. Figure 67 shows these spot welds black boxes. After processing with the high-pressure waterjet, no additional spot-welds were broken or cracked.

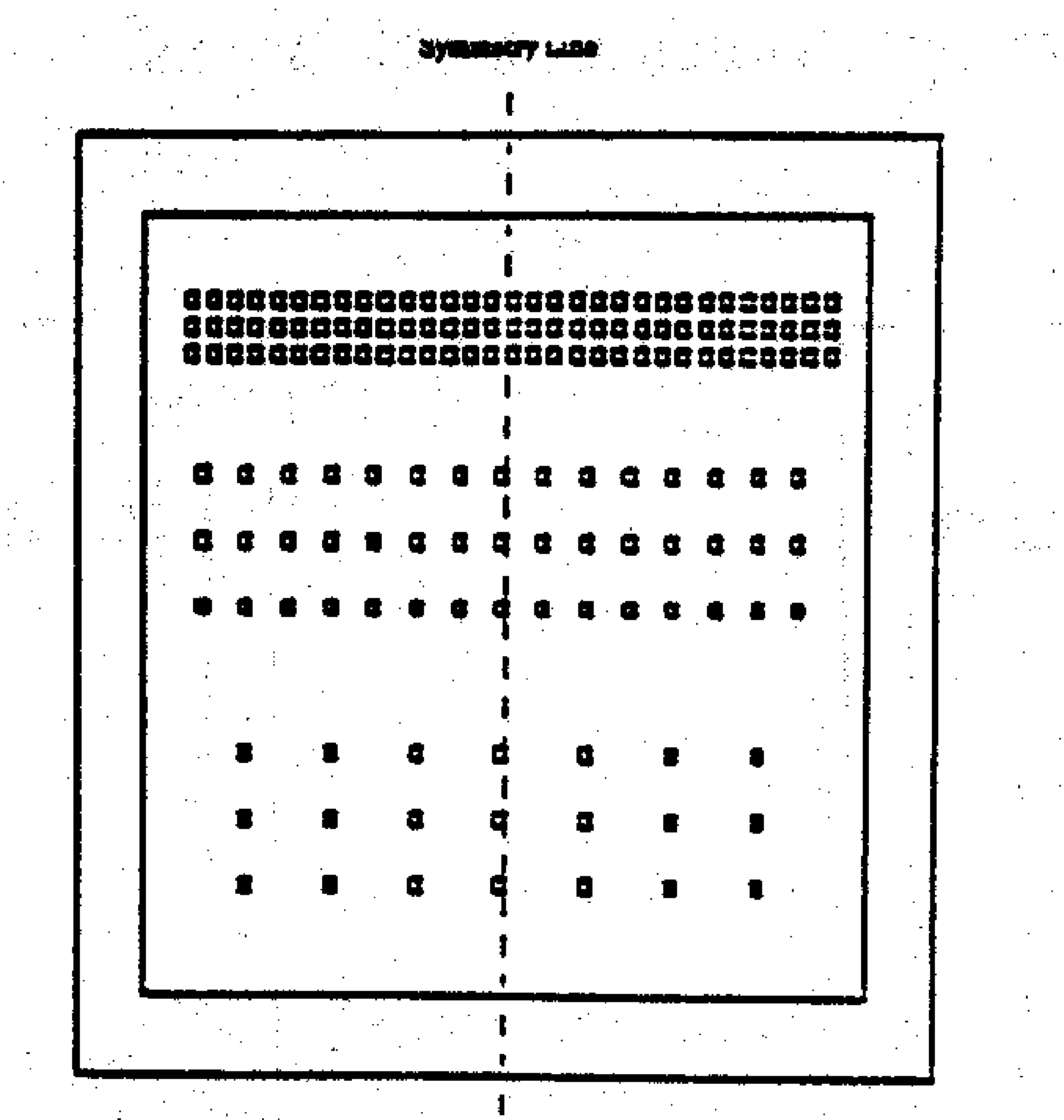


Figure 67. Baseline for bent weld panel: 2024-T3 alclad, 0.032-inch.

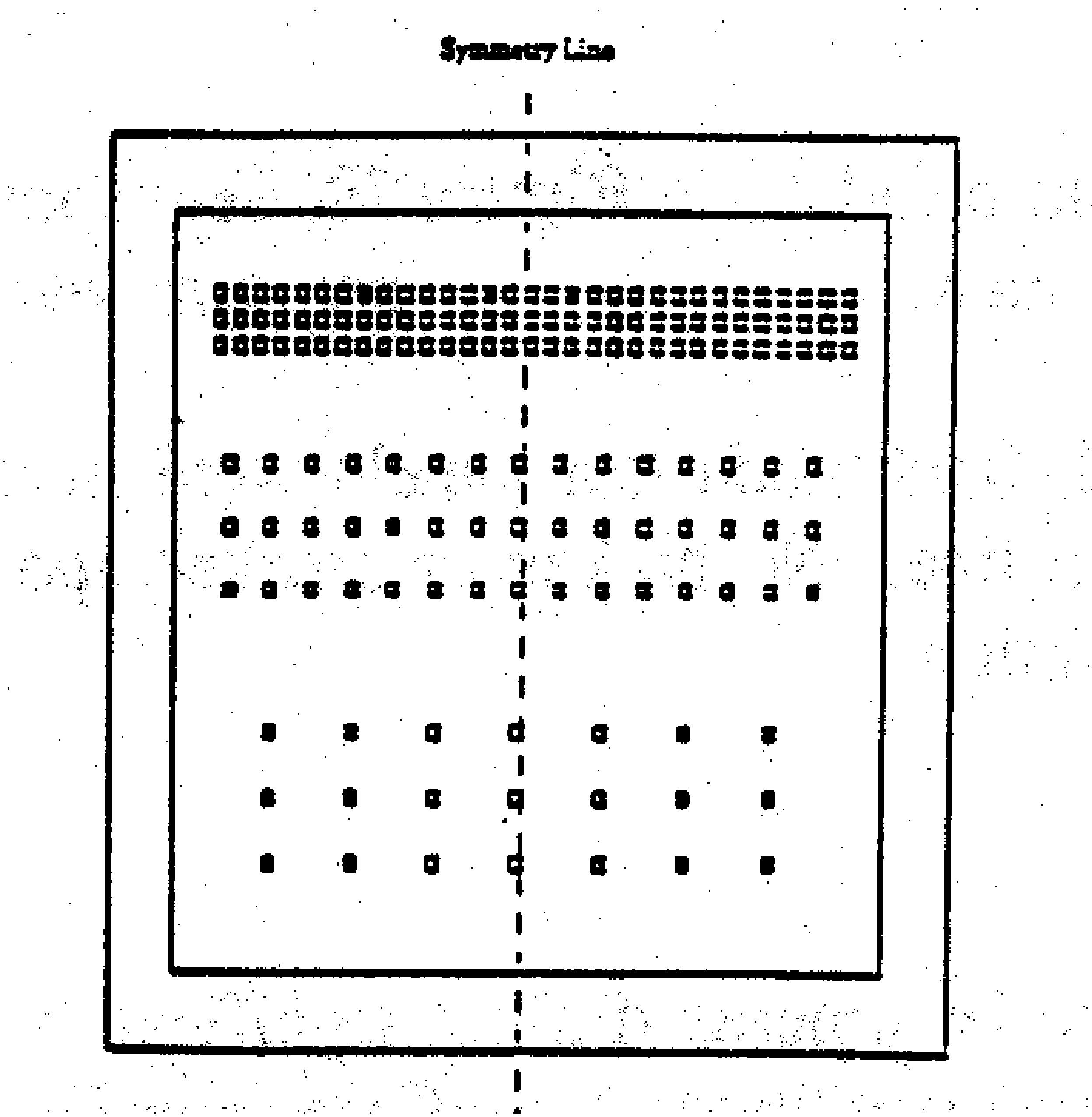


Figure 68. Bent spot weld panel processed with high-pressure waterjet: 2024-T3 alclad, 0.032-inch.

b. Al 2024-T3 alclad, 0.080-inch test panels were inspected after painting but before processing to establish the baseline. No broken or cracked spot welds were found for the pre-process condition. However, after high-pressure waterjet processing, three spot welds were cracked or broken where the pitch was 0.25 inch. Figure 68 shows these spot welds as black boxes.

c. Al 7075-T6 Alclad, 0.032-inch test panels were inspected after painting but before

processing to establish the baseline. Seventy-two broken or cracked spot welds for all pitch sizes were found for the pre-process condition. The distribution of broken or cracked spot welds included 12 from the 1.0-inch pitch area, 18 from the 0.5-inch pitch area, and 42 from the 0.25-inch pitch area. This large number of broken or cracked spot welds is probably related to the development of thermal stresses in the bent panel after artificial aging during the cool down. Because it was fabricated from 0.032-inch-thick metal, the panel was able to undergo deflection during cool down, resulting in spot welds breaking or cracking. Figure 69 shows these spot welds as black boxes. After high-pressure waterjet processing, 81 spot welds were cracked or broken. Figure 70 shows these spot welds as black boxes.

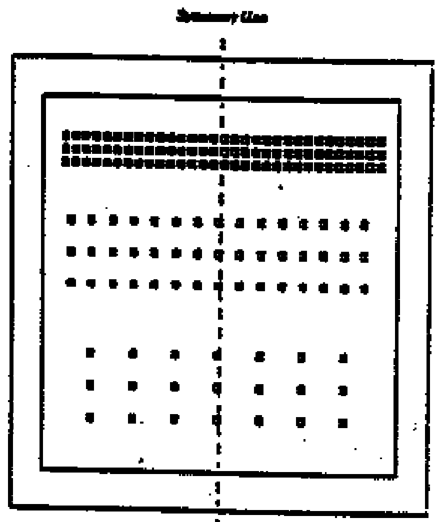


Figure 69. Baseline spot weld panel: 7075-T6 alclad, 0.032-inch.

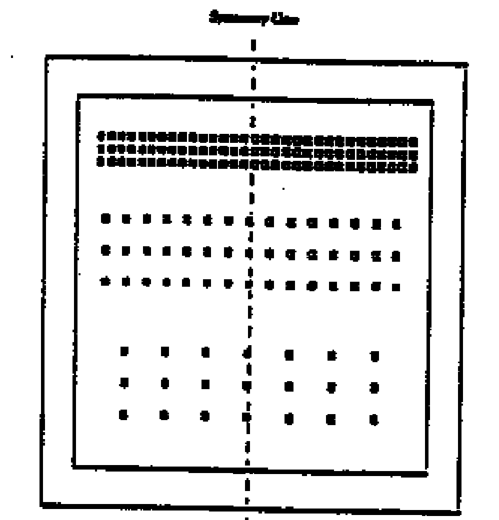


Figure 70. Bent spot weld panel processed with high pressure waterjet: 7075-T6, 0.032 inch.

d. Al 7075-T6 alclad, 0.080-inch test panels were inspected after painting but before processing to establish the baseline. No broken or cracked spot welds were found for the pre-process and post-process condition.

4.10.6.3 Summary.

The high-pressure waterjet process did not significantly change the spot weld integrity compared to the baseline/painted condition. Significant numbers of spot welds were broken for the bent panel configuration, which probably related to the development of thermal stresses in the panel after the artificial aging during cool down.

4.11 CONCLUSIONS

To date, the testing during process validation has shown the following:

4.11.1 Fatigue, Unnotched 100,000 Cycles.

- **The high-pressure waterjet process has no significant effect on the fatigue life of 2024-T3 clad and 7075-T6 clad over the current chemical stripping process.**

- **The high-pressure waterjet process has a higher fatigue life than the current chemical stripping process for 2024-T3 bare and 7075-T6 bare.**

- **Artificial aging appears to decrease the fatigue life of 2024-T3 coupons but not the 7075-T6 coupons. This reduction is probably related to the aging temperature being greater than the natural aging temperature for 2024-T3 coupons but lower than the precipitation aging temperature for the 7075-T6 coupons.**

4.11.2 Fatigue, Unnotched 500,000 Cycles.

- **The high-pressure waterjet process has no significant effect on the fatigue life of 2024-T3 clad and 7075-T6 clad over the current chemical stripping process.**

- **The high-pressure waterjet process produces a higher fatigue life than the current chemical stripping process for 2024-T3 bare and 7075-T6 bare.**

- **Artificial aging appears to decrease the fatigue life of 2024-T3 coupons but not 7075-T6 coupons. This reduction probably is related to the aging temperature being greater than the natural aging temperature for 2024-T3 coupons but lower than the precipitation aging temperature for the 7075-T6 coupons.**

4.11.3 Fatigue, Notched Front.

- **Coupon preparation significantly affected the fatigue life of notched coupons. These tests are being repeated using coupons notched by OC-ALC.**

4.11.4 Fatigue, Notched Back.

- **Coupon preparation significantly affected the fatigue life of the notched coupons. These tests are being repeated using coupons notched by OC-ALC.**

4.11.5 FCGR.

- **High-pressure waterjet processing did not reduce the fatigue life of 2024-T3 clad, 2024-T3 bare, 7075-T6 clad, or 7075-T6 bare when compared to chemical stripping.**

4.11.6 Salt Fog Corrosion.

- **High-pressure waterjet processing did not affect the salt fog corrosion behavior of the aluminum alloys when compared to unprocessed or chemically stripped coupons.**

4.11.7 Repaintability.

- **High-pressure waterjet processing did not affect the paint adhesion of aluminum alloys when compared to pre-processed or chemically stripped coupons.**

4.11.8 Spot Weld Integrity.

- **High-pressure waterjet processing did not affect the spot weld integrity of aluminum.**

SECTION V - U.S. NAVY HIGH-PRESSURE WATERJET DEMONSTRATION

5.1 DESCRIPTION

5.1.1 The entire system, which is totally mobile and self-contained for dry-dock, shipyard, or harbor operation, is transported on wheeled trailers. Basic system elements include a high-pressure water pump, a telescoping transporter with a 5-axis telescoping arm, a 6-axis manipulator with a specialized end effector, a recovery process trailer, and a system remote control console. The end effector incorporates a 6-inch-wide water jet nozzle in a frame designed for precise application of the water's energy against the side of the ship. The frame guides the stripping paths mechanically. by the frame. The end effector has the ability to comply with various surface contours on ship hulls. It also incorporates an effluent containment shroud around the waterjet nozzle and a strong vacuum. These components completely contain all process water and coating residue and transfer them to the water reclamation unit.

5.1.2 For closed-loop operation, the system includes a modular water reclamation subsystem that filters all waste water and recycles cleaned water to the high-pressure water pump. The only waste products generated are the removed coating and any fouling.

5.2 ADVANTAGES

The closed-loop waterjet process is superior to conventional marine coating removal methods (grit blasting, shot peening, sanding, chipping, scraping, brushing, etc.) and offers the following advantages:

- **Produces no dust or airborne contaminants.**
- **Requires no containment structures.**
- **Does not subject workers or the environment to hazardous waste.**
- **Effectively removes surface contaminants such as salt.**
- **Allows other maintenance operations to be performed simultaneously.**
- **Leaves stripped surfaces clean and dry.**
- **Requires no cleanup after stripping.**
- **Lowers manpower requirements.**
- **Allows repainting with no additional surface preparation.**
- **Meets all environmental requirements and promises large cost savings.**

5.3 SPECIFICATIONS

The Navy Waterjet Demonstration System (NWDS) consists of an end effector subsystem (nozzle, effluent recovery shroud, and nozzle rotation drive and controls), a high-pressure pump, an effluent recovery and water reclamation system, a manipulator, and a transporter.

5.3.1 End Effector Subsystem.

The end effector subsystem is a self-contained nozzle and shroud assembly with a hydraulically controlled, Even-EnergyÔ, 6-inch-wide stripping nozzle.

5.3.1.1 Nozzle.

The Even-EnergyÔ nozzle contains more than 20 laser-drilled industrial sapphire orifices that vary in size and placement to provide even energy distribution. The nozzle body does not wear because of the water flow. The orifices within the nozzle body are the only consumable items and are easily replaced with a common allen wrench.

5.3.1.2 Vacuum Recovery Shroud.

The vacuum recovery shroud is designed to capture virtually 100 percent of the process water and the suspended paint particles and fouling residue. The vacuum shroud quickly removes all effluent so the stripping efficiency of the nozzle does not diminish as the end effector progresses along the hull. As it removes the process effluent, the vacuum simultaneously dries the substrate, leaving it rust free.

5.3.1.3 Compliance and Standoff Control.

A mechanical device is built into the end effector's frame to control standoff distance. This device ensures continuous surface contact and efficient effluent capture over large variations of curved surfaces.

5.3.1.4 Hydraulic Drive.

The transporter’s hydraulic power unit rotates the waterjet nozzle by supplying hydraulic fluid to a motor in the end effector. The motor drives a high-pressure water swivel that rotates the nozzle. Hydraulic power was selected over other types of drives because of its higher starting torque, accuracy, and proven reliability.

5.3.2 Manipulator Subsystem.

The manipulator subsystem provides the interface between the ship’s surface and the end effector. The end effector moves back and forth across the manipulator’s 4.5- by 6.5-foot working envelope while maintaining hull contact to ensure that the vacuum recovery head captures all effluents.

5.3.3 Transporter Subsystem.

An off-the-shelf, mobile, telescoping transporter subsystem accurately positions and repositions the manipulator against the ship's hull. The transporter is capable of reaching 60 feet high with 360 degrees of continuous rotation. All process hoses and cables are routed along the boom.

5.3.3.1 Remote Control Console.

A console, giving the operator a single point from which to control all subsystems, is mounted on a roll-around cart so it can be positioned for maximum operator convenience and visibility.

5.3.3.2 Auxiliary Power Generator.

A separate power generator also is provided with the transporter for operating the manipulator and the control console.

5.3.4 High-Pressure Pump Subsystem.

5.3.4.1 A high-pressure, dual intensifier water pump carried on a separate small trailer supplies water to the end effector at the required pressure and volume for the stripping operation. The pumping unit is self-contained, diesel powered, and well suited to the task of stripping thick, tough coatings (anti-foulant topcoat, marine growths, epoxy primer, etc.). It also is capable of supplying water to the end effector at up to 10 gallons per minute (GPM) and 36,000 psi. All pressure hoses, tubes and fittings are burst rated at 90,000 psi.

5.3.4.2 A hydraulic system drives dual, plunger-type intensifiers as part of a closed-loop system. The intensifiers are easily accessible for maintenance and repair. The hydraulic system includes an integral full-flow filtration system, hydraulic reservoir, and pressure gauges.

5.3.4.3 The operator turns the pump's intensifier on and off and regulates pressure from the remote control console. The pump also can be manually operated at a control panel on the pump's face. An automatic protection feature monitors critical pump functions and warns the operator of abnormal parameters.

5.3.5 Effluent Recovery Subsystem.

5.3.5.1 The effluent recovery system collects process water, paint, and fouling residue. This system filters the paint and residue, removing leached ions (copper, cadmium, lead, etc.), micro-particulates, chlorides, sulfates, nitrates, and other contaminants picked up from the surface being stripped. This mobile subsystem is installed in a standard shipping container and chassis.

5.3.5.2 The effluent first enters the recovery system through a 6-inch vacuum recovery hose attached to the shroud around the nozzle. A dri-prime pump removes the material from the bottom chamber of the vacuum and deposits it into a vibrating liquid/solid separator. The separator acts as a "shaker," removing about 95 percent of the solid material. The liquid is then pumped to a micro-separator, which is the first stage of the water reclamation unit. The micro-separator uses centrifugal force to remove all material heavier than water. Then it passes the water through a coalescing tank (to remove oils and film), an ozone generator, charcoal filter, micro-filters, and finally a deionization system with conductivity meter to make sure the water recycled to the pump is Grade A deionized water.

5.3.5.3 Utility Trailer.

To provide mobility in the limited space of shipyards and dry docks, the effluent recovery subsystem is installed in a standard shipping container (approximately 40-feet long by 13.6-feet tall and 8-feet wide). The container can be removed from the chassis and placed flat on the dry-dock floor or supported at each corner by a dual-wheeled caster. The container can be moved on this caster with a forklift and tow bar.

5.3.5.4 Vacuum Unit.

A high-powered wet/dry vacuum unit recovers nearly 100 percent of the process water as the coating is removed. The liquid/solid slurry is captured in a removable hopper under the vacuum unit in the process trailer. The entrained air is filtered and exhausted to the atmosphere.

5.3.5.5 Sump Pump.

A dri-prime pump removes the liquid/solid slurry from the vacuum collection hopper and pumps it to the liquid/solid separator. The pump is capable of handling liquid slurries with solids up to 1.5 inches in diameter.

5.3.5.6 Liquid/Solid Separator.

Because of the large amount of solid waste material encountered in stripping a large ship, a customized liquid/solid separator is used to pre-process the effluent before transferring it to the water reclamation unit. An adjustable mesh, vibrating screen separates most of the solids from the liquid. Those solids are dumped into a 55-gallon drum for disposal. The remaining dirty water is captured in a collection tank before being pumped to the water reclamation unit for further filtering and treatment.

5.3.5.7 Water Reclamation Unit.

A modular water reclamation unit filters and conditions the used process water and returns it to the high-pressure water pump. A sump pump first directs the water to a centrifugal separator, which removes most of the particulate. The water from the centrifugal

separator then goes into a 300-gallon raw water tank. The raw water is pumped through a series of filters, an oil separator, and an ozone generator before being deposited into a 200-gallon clear well tank. The water in the clear well tank then passes through deionization tanks to remove heavy metals, then through a final 0.35-micron filter before reuse by the system's high-pressure water pump. To compensate for evaporation losses, potable water is automatically added from the system's make-up tank.

5.3.5.8 Generator.

A diesel-powered electric generator powers the vacuum unit, water reclamation unit, air compressor, dri-prime pump, liquid/solid separator, and other trailer utilities.

5.3.5.9 Air Compressor.

An air compressor supplies air for operation of the manipulator, pumps, valves, and utility equipment.

5.3.5.10 Panel Tests.

As part of the NWDS effort, 40 panels were tested to evaluate paint removal rates, remaining surface contaminants, and paint adhesion after waterjet processing. Specific areas of evaluation included:

- **Assess waterjet effects and variation in removal rates from various tooth profiles.**
- **Evaluating effects of paint thickness on removal rates.**
- **Assessing how various percentages of paint left on the surface after stripping affect paint adhesion.**
- **Determining any adverse effects of waterjet processing from salt-fog and pull-adhesion tests.**

5.4 SHIPYARD TEST AND DEMONSTRATION

5.4.1 The system was moved to Puget Sound Naval Shipyard (NSY) on 18 Jul 94. Its first test at the yard was the removal of about 500 ft^2 of underwater hull paint from the USS NIMITZ (CVN 68).

5.4.2 Two coats of international EP-Series anticorrosive paint and four coats of international BRA series antifoulant paint were applied to the USS NIMITZ's underwater hull. The coatings, which had been on for less than 4 years, averaged 30-40 mils thick and were in excellent shape. The ship was sent back out with the paint system intact except in the areas where tests were performed with the high-pressure waterjet demonstration system and a few other limited areas.

5.4.3 This was the first test of the system on a ship, so the process parameters had not yet been optimized, but the removal rate achieved was 136 ft^2 per hour. This rate does not include time to move the manipulator from location to location on the hull. It only includes the time to remove paint from a 4.5- by 6.5-foot envelope. Although the frame only takes a few minutes to reposition, this time is not included in any of the rates mentioned in this section.

5.4.4 The vacuum recovery shroud performed extremely well and, after some minor adjustments, it recovered 100 percent of the effluent. Another significant benefit was that the bare metal did not flash rust following paint removal. This was a result of the strong vacuum and heat (about 120° F) created by the water energy, which causes the steel to dry very quickly, eliminating the potential for flash rusting on the surface.

5.4.5 In Oct 94, the system was moved to Pearl Harbor Naval Shipyard (NSY), Hawaii. The Commander in Chief, Pacific Fleet requested the system be used on the USS LEFTWICH (DD 984) to expedite the non-organotin paint removal. The hull paint above the water line was stripped. Two crews of operators (one blast controller and one maintenance mechanic per shift) from Puget Sound NSY, Bremerton, WA, operated the system for two 10-hour shifts per day. Approximately 18,000 ft^2 of paint were removed during this job. USS LEFTWICH had a 5-coat paint system averaging about 20 mils thickness that consisted of a Catha Coat zinc-rich epoxy base coat followed by an F150 epoxy coat and an F153 epoxy coat topped with two haze gray coats of TT-E-490 silicon alkyd.

5.4.6 The USS LEFTWICH job showcased the unique capabilities of this system. The underwater hull had organotin antifoulant paint requiring removal in custom-built enclosures. To meet the established production schedule, the paint above the water line had to be removed at the same time as the underwater hull paint. This was not possible with conventional coating removal techniques, because the organotin enclosures obstructed work above the water line. Additionally, use of the NWDS allowed shipyard personnel to repaint the hull removing paint in adjacent areas.

5.5 FUTURE PLANS

5.5.1 During operation at Pearl Harbor, the Navy gained invaluable experience in operating and maintaining the system. This experience is being used to design a retrofit package for installation at Long Beach NSY, CA. The goal of this retrofit package is to increase the operational availability of the system by solving problems that have caused repeated down time and by increasing ease of maintaining other system components.

5.5.2 Two enhancements currently under design will also be ready for use at Long Beach NSY. The first is an interface to mate the Navy designed ultra high-pressure water garnet injection nozzle to the demonstration system. This enhancement will add the capability to generate an anchor tooth profile on hull areas that have rusted or have been welded. This capability is needed because the standard pure water nozzle only exposes the existing profile. The second enhancement will be hand-held, closed-loop high-pressure waterjet stripping

units. These units will use the same services (water, vacuum, etc.) as the initial design but will add the capability to reach tight areas, such as between keel blocks and around pad eyes and hull openings.